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The Relationship of Sector Characteristics to Operational Errors

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16. Abstract

An exploratory study was conducted on the relationship of air traffic control (ATC) complexity factors to operational errors (OEs). This consisted of a detailed examination of OE data from 1992 through 1995 from the Atlanta en route center. The Systematic Air Traffic Operations Research Initiative (SATORI) system was used to collect data for the analysis. Sectors were categorized into zero-, low-, and high-error groups. Fifteen sector and traffic flow variables had statistically significant correlations with OE frequency. Four variables were higher for the high-error group as compared to the zero-error group. Sector size was smaller for the high-error group as compared to the combined zero- and low-error categories. A significant multiple correlation was found between overall OE rate and a subset of the ATC complexity measures. The data were also analyzed to define relationships between the complexity measures and controller situational awareness (SA) at the time of the OE. The only statistically significant difference between OEs with and without SA was for horizontal separation. In addition, high-error sectors were characterized by low SA for errors. Certain sector and traffic flow characteristics were associated with these high-error sectors, suggesting that these factors may negatively affect SA. It was concluded that the results demonstrated a relationship between sector complexity and OE rate. Such findings, if extended, could assist with traffic management, sector design activities, and the development of decision-support systems.

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EXECUTIVE SUMMARY

A study of air traffic control (ATC) complexity issues associated with the causes of operational errors (OEs) in the National Airspace System was conducted. It consisted of a comprehensive survey of the literature on OEs and a detailed analysis of OE data from the years 1992 through 1995 from Atlanta's Air Route Traffic Control Center (ARTCC). Of specific concern was the influence of airspace sectorization and traffic characteristics on OE incidence. The Systematic Air Traffic Operations Research Initiative (SATORI) system and other methods were used to collect data for the analysis.

The literature review was conducted on the relationship of airspace and air traffic factors to OE occurrence. Papers were analyzed for information that might help identify sector characteristics or aircraft flow patterns (also known as ATC complexity factors) that could lead to a loss of separation between aircraft. It was found that very little research has directly addressed the issue of ATC complexity as a factor in OE occurrence. A possible reason cited was that most prior investigation has focused on the analysis of OE database information that is lacking in specific details on causality. Nevertheless, there was evidence that sector and traffic characteristics could influence workload and error incidence.

A theme in the literature emerged with regard to the relationship of sector design and the amount of coordination controllers must perform. Many studies cited coordination problems as a factor in OEs. Additional issues from the literature review were evaluated for their role in creating the conditions for OEs. These data came from both theoretical and empirical research studies. The information extracted from the literature review was used to guide the research at the Atlanta ARTCC.

Data from SATORI, a complexity factor questionnaire, the 1995 facility review, and OE reports were combined in a database. Descriptive information was computed for error causality and sector characteristics. A factor analysis of the sector variables yielded six dimensions, the most important being the first three: Traffic Activity, Size, and Military. OE conditions were described as a function of time of day, flight level, traffic density, complexity, vertical and horizontal separation, severity, workload, number of controllers working, and situation awareness (SA).

The 45 sectors in the Atlanta ARTCC were categorized into No-, Low-, and High-Error groups. The data collected on sector and traffic flow characteristics were used to explore differences between groups that might account for OE incidence. Fifteen variables had statistically significant (or marginally significant) correlations with error frequency. Further analyses indicated that four variables (Weather, Radio Frequency Congestion, Total Complexity, and Average Complexity) were higher for the High-error group as compared to the Low-error group. Sector size was smaller for the High-error group, as compared to the combined No- and Low-error categories. Four other variables showed marginally significant differences between groups.

Using several related statistical techniques, it was possible to demonstrate that overall OE rate or sector severity group could be predicted by a subset of the sector characteristic and traffic flow variables. However, although there was statistical significance, accuracies were generally low, indicating insufficient power for practical applications. Nevertheless, a firm theoretical relationship was demonstrated between sector complexity and OE occurrence.

The data were also analyzed to define relationships between sector and traffic flow characteristics and controller situational awareness at the time of the error. The only statistically significant variable was horizontal separation; more horizontal separation was found for errors where SA was present. Errors where controllers reported that they were not aware of the impending loss of separation occurred when there were more military operational restrictions. Also, as

sector error count increased, there was a greater proportion of errors were the controller did not have SA. Thus, high-error rate sectors were characterized by low SA for error development.

The results of the data analysis were reviewed for relationships to the literature survey. Of note was the 24% increase in error causation assigned to problems with the radar display. Previous research found that most errors occurred in low to moderate workload. The current data set showed that errors were reported with an average of eight aircraft in the sector and with moderate complexity. This density level was significantly higher than the base rate of 6.5 aircraft. It was not possible to explore the issue of coordination problems extensively. There was some indication that sectors with climbing and descending traffic experienced more OEs, thus corroborating some previous findings.

It was concluded that further data on normal Atlanta ARTCC traffic flows are needed to determine if OE frequencies departed from expected proportions. The factor analysis produced useful information about the underlying dimensions (Traffic Activity, Military, and Size) characterizing sectors. One facility review variable, Average Density, was not related to other traffic load measures. This warrants further study. Several results demonstrated a relationship between sector complexity and OE rate. Such findings, when validated, could assist with traffic management and sector design activities.

Given the importance of situation awareness for avoiding operational errors, evidence was found that increased sector complexity may be associated with reduced situation awareness and may lead to a larger number of, and more severe, errors.

THE RELATIONSHIP OF SECTOR CHARACTERISTICS TO OPERATIONAL ERRORS

1. PURPOSE

A research project was conducted on sector design and operational errors (OEs) in en route air traffic control (ATC) sponsored by the Federal Aviation Administration's (FAA's) Civil Aeromedical Institute (CAMI). The goal of the study was to employ the Systematic Air Traffic Operations Research Initiative (SATORI) system and other sources of data on en route ATC sectors to investigate possible underlying causes of OEs in the Atlanta Air Route Traffic Control Center (ARTCC).

2. INTRODUCTION

In the history of the FAA, no aircraft have collided while under positive control in en route airspace. However, aircraft have violated prescribed separation minima and approached in close proximity. This event can occur as a result of either a pilot deviation or an OE. An OE takes place when an air traffic controller allows less than applicable minimum separation criteria between aircraft (or an aircraft and an obstruction). The number of OEs is a primary index of National Airspace System (NAS) safety.

Standards for separation minima are described in the ATC Handbook (FAA Order 7110.65, and supplemental instructions). While there is considerable complexity in those standards, at flight levels between 29,000 feet (ft) and 45,000 ft, Air Traffic Control Specialists (ATCSs) at en route facilities are required to maintain either 2,000 ft vertical separation or 5 miles (mi) horizontal separation between aircraft. At flight levels below 29,000 ft with aircraft under instrument flight rules, ATCSs are required to maintain either 1000 ft vertical separation or 5 mi horizontal separation.

Immediately after the detection of an OE, a detailed investigation is conducted in an attempt to fully describe the events associated with the error's occurrence. This includes removing the ATCS(s) from the operating position and obtaining a statement from each of the involved personnel, gathering the relevant data (voice and computer tapes), and reviewing in detail the events associated with the error's occurrence. At the Atlanta ARTCC, the SATORI system is used to re-create the error situation in a format much like the one originally displayed to the ATCS (Rodgers and Duke, 1993). SATORI allows for a more accurate determination of the factors involved in the incident. Once the OE has been thoroughly investigated, an OE Final Report is filed. This report, the Final Operational Error/Deviation Report (FAA 7210.3), contains detailed information about each error obtained during the investigation process.

The responsibility for the occurrence of an OE, except in cases of equipment outage or deficient procedures, ultimately rests with the air traffic controller who must detect and resolve potential conflicts before they become errors. However, in many error analyses, such problems are blamed on some type of human failure without a deeper investigation of other contributing factors. It has been the role of the human factors discipline to address how computer-human interface (CHI) characteristics can create impediments to task performance, resulting in errors. This project extends this approach to consider characteristics of the task domain or environment that could increase the chances of error.

The discussion of airspace and traffic characteristics in this paper is based on the concept of ATC complexity (Mogford, Guttman, Morrow, & Kopardekar, 1995). This construct incorporates the physical aspects of a sector, such as size or airway configuration, and factors relating to the movement of air traffic through the airspace, such as number of climbing and descending flights. Past research has identified specific airspace and traffic factors that contribute to ATC complexity (Mogford, Murphy, Yastrop, Guttman, & Roske-Hofstrand, 1993).

As shown in Figure 1, ATC complexity is the underlying driver of controller workload. The procedures required in the sector, flight plans, traffic load, weather, and other variables form the basis for the tasks the controller must complete. Although evidence is weak, controller workload is probably associated with OE commission. As task information processing requirements reach and exceed controller sensory and cognitive capacities, aircraft may not receive sufficient attention and control to maintain required separation. Workload may be increased through the presence and interaction of several complexity factors that create competition for similar cognitive resources. Alternately, isolated ATC complexity factors may lead to unsafe conditions by placing focused demands on the controller. Such factors may be transitory or sustained and may pose undue strain on specific information processing channels or capabilities (such as memory). For example, the management of a sector may require the application of many required procedures. Forgetting to apply these at the correct time could lead to traffic problems, and errors.

The amount of workload experienced by the controller is affected by the information processing strategies adopted to accomplish required tasks. Such techniques may have been learned in developmental training or evolved on the job and may vary in effectiveness. The influence of a complex ATC environment on workload can be ameliorated through the use of strategies that maintain safety through, for example, simpler or more precise actions.

Also relevant is the effect of equipment on workload. The controller's job will be made easier if a good user interface is provided. This will ensure that adequate and accurate information is presented to support efficient task completion. Automation tools to support essential tasks should also be available. It is for this reason that the FAA is developing decision support systems to facilitate more effective control actions.

Workload can also be influenced by personal variables, such as age, susceptibility to anxiety, and amount of experience. Variations in skill between controllers can be quite pronounced. These factors can have a strong effect on the workload experienced by a given controller in response to a specific array of ATC complexity factors.

The goal of this research was to isolate those ATC complexity factors that create the conditions for OEs. This is not to minimize the possible effects of other CHI and operator-specific factors. Rather, it is to begin to fill a research void on ATC errors concerning the effects of the controller's work domain: air traffic, airspace, and their characteristics.

The paper is divided into two sections. The first contains a brief literature review on OEs and their causes. The second section discusses an analysis of data available on OEs from the Atlanta ARTCC and their relationship to sector and traffic characteristics.

The research was exploratory in nature and consisted of a variety of analyses intended to map relationships in the data. Exploratory data analysis focuses on generating theoretical models from data, rather than testing a pre-existing model. By exploring the data with an inquisitive mind, it is possible to discover what is not necessarily expected. Visual representations (such as graphs) and the use of statistics that are resistant to the effects of departures from assumptions (such that variables are normally distributed) are used. However, one outcome of using several statistical tests with the same data set is an increased chance of finding statistically significant differences where there are none. As a result, the statistical findings in this report should be considered as tentative pending a larger-scale study.

3. LITERATURE REVIEW

3.1 Scope

This review examines the research completed to date on the causes of OEs. Literature sources included the FAA Technical Center Library, FAA Headquarters Library, FAA CAMI Library, PsychINFO (an online database service of Compuserve), National Technical Information Service database, and Embry-Riddle Aeronautical University Library. Keyword searches were conducted to identify publications concerning ATC operational errors and sector design.

The emphasis of the literature review was on airspace- and traffic-related factors that contribute to OE occurrence. Although the papers discussed contained information on other factors that affect error frequency, they were not the focus of this effort. As much as possible, the contents of each reference were screened for insights on how sector design, traffic flow patterns, procedures (such as those found in Letters of Agreement [LOAs]), and other airspace factors cause, relate to, or affect OE incidence. Other research findings or hypotheses were only reported as needed to support the discussion of this theme.

3.2 Summary of the Literature

Several of the reviewed papers discussed theoretically-derived airspace issues that could be related to OEs. For example, Arad (1964a) conducted an analytical and empirical study of workload in relation to sector design. He divided controller workload into three categories: the background load involved in working the position, independent of aircraft activity; the routine load of controlling a "standard" aircraft, irrespective of its interactions with other aircraft; and the airspace load imposed by the natural tendency of uncontrolled traffic, in a free-flow environment, to converge in unsafe ways, thus requiring control actions.

Arad (1964a) developed a mathematical expression that he suggested would account for the number of aircraft conflicts. The variables in the equation included rules of separation, average traffic speed, number of aircraft under control, sector size, and flow organization. The last term was not clearly defined, but was described as "a number that quantifies the flow organization and numerically relates the variables... to the actual numerical value of the conflict rate..." (p. 29).

A report by Arad (1964b) described further work on the analysis of the above load factors and suggested that sector design could greatly affect the routine load imposed on the controller. For example, if traffic flow tends to be north/south, then establishing sector boundaries parallel with flow imposes less work on controllers than if they are established east/west, or perpendicular to the traffic flow. Therefore, a rectangular sector with its long side parallel with the direction of traffic flow is most efficient if traffic tends to flow in one direction. If traffic flow is more random, a circular-shaped sector is more effective and will presumably result in fewer OEs.

Along similar lines to these papers, Siddiqee (1973) attempted to develop a mathematical model for predicting the expected duration of aircraft conflicts at air route intersections. The equations are not relevant for this review, but one of the author's assumptions is noteworthy:

> ...in the en route environment, aircraft fly essentially level at certain standard altitudes. The standard altitude increments used are large enough to ensure adequate vertical separation, with allowance for flight technical, altimeter, and pilot errors. Thus, in en route environments, conflict situations arise mainly because of loss of the horizontal separation among aircraft flying at the same altitudes. (p. 59)

Schmidt (1976) described a sector workload model intended to aid in the design and evaluation of airspace. The author defined ATC workload as "the frequency of occurrence of events which require decisions to be made and actions to be taken by the controller team, and the time required to accomplish the tasks associated with these events" (p. 531). Event categories included potential conflicts between aircraft at air route intersections, potential aircraft-overtaking conflicts along air routes, and routine procedural events.

Schmidt (1976) noted that the expected frequency and duration of crossing and overtaking conflicts can be predicted by traffic flow rate, aircraft separation standards, route geometry, and aircraft velocity. Conflicts at an air route intersection are related to aircraft flow rate, velocity along each route, minimum aircraft separation requirements, angle of intersection between the routes, and number of flight levels. The author developed equations that purportedly would predict conflict event frequency and added that the amount of transitioning traffic had to be factored into the calculation.

Couluris and Schmidt (1973) noted that sector design can affect controller workload and, presumably, the potential for OE occurrence. Number of handoffs, coordination, pointouts, and structuring and bookkeeping events:

> ...result from, or are influenced by, the existence and design (shape) of the sectors. The additional work created can be thought of as the cost of sectorization. Although they are still related to traffic and route parameters, they can be varied. For example, a sector boundary that crosses a highly traveled route will create a larger work load (from the above four work-producing event types) than a boundary across a sparsely traveled route. (p. 657)

This research suggests that sector structure, in terms of boundary location and shape, airway configuration, and intersections, can affect conflict frequency. Such factors as traffic flow rate, average velocity, separation requirements, number of flight levels, and transitioning traffic can also influence outcomes.

The following studies sought to classify air traffic controller errors and may shed some light on possible sector-related causes of OEs. They were screened for possible factors that could help orient the SATORI-based research on Atlanta ARTCC airspace.

Empson (1987) applied a human error classification system to military air traffic controllers in the United Kingdom over a two-year period. The subjects performed two distinct roles, that of radar director and radar approach. The radar director controller gave heading and altitude instructions to aircraft, kept them separated, and sequenced them for approaches to the airfield. The radar approach controller was responsible for aircraft within a 30-mile radius of the field and initially identified aircraft inbound for landing. This person also handled aircraft departing from the field. The radar director was responsible for flights nearing the field while the approach controllers handled aircraft within the approach area. Approach controllers handled about twice as much traffic as the directors.

Eight controllers (four in each category) were observed over two, 2½-hour periods. A total of 131 errors were observed and categorized as discrimination errors, program-based (or action-related) errors, and errors relating to memory functions. Errors made by directors were higher than for approach controllers. This was in spite of the fact that directors had aircraft on frequency 36 percent of the time compared with 79 percent for approach controllers. The error rate for both controller types increased with traffic load.

The author suggested the reason for these results might be that the director's job was more difficult. The director typically had to accept fast reconnaissance jets that were low on fuel and sequence them for handoff for landing. Handoffs had to occur at a precise heading and altitude. The approach controller, on the other hand, experienced much less time pressure and dealt with aircraft with various destinations. In a related paper by Langan-Fox and Empson (1985), it was suggested that another reason for the higher workload in the director position could be that the director tasks were force-paced. That is, in the case of the approach controller, the presentation rate of events were system controlled as opposed to worker controlled (self-paced). Other research (Bertelson, Boone, and Renkin, 1965) demonstrated almost error-free performance for workers in a self-paced work setting but showed a dramatic increase in error rates when the self-pace rates were imposed upon the operators.

This research, apart from being a useful application of a human error taxonomy, demonstrates possible effects of airspace structure, procedural demands, task characteristics, and traffic type on controller errors. The findings support the assumption that an analysis of such features can lead to a better understanding of controller error.

In contrast to these observations of working controllers, the following papers focused on the analysis of OE databases.

Kinney, Spahn, and Amato (1977) conducted a study of system errors as recorded in the US System Effectiveness Information System (SEIS) for the years 1974, 1975, and 1976. The data for en route centers showed that, of the 564 errors recorded for the 3 years, 95% of direct causes were attributed to attention, judgment, or communications. The same categories accounted for 71% of contributing causes. Other contributing factors included stress (0.2%), equipment

(6%), operations management (5%), environment (such as receipt of erroneous information or lack of compliance from pilots, user equipment failures, or heavy controller workload) (1%), procedures (2%), external (9%), and no code (6%).

Only one of the error categories (procedures) relates to sector factors. This was subdivided into six sub-categories according to whether the procedure was inadequate, too complex, impractical, etc.

Kinney, et al. (1977) also examined system errors in the context of reported controller workload. Traffic volume and workload complexity at the time of occurrence of the error were subjectively rated as light, moderate, or heavy. As Table 1 shows, most incidents occurred under conditions of light or moderate volume and moderate workload complexity in the 1974-76 SEIS data.

Other findings by Kinney, et al. (1977) showed no relationship between errors and previous errors by the same controller or between errors and controller age. There was an indication in the 1976 data that controllers with more than 5 but less than ten years of employment with the FAA experienced more problems. Controllers with less than 24 months of work history in their current positions were slightly more error prone. Finally, of those errors reported in en route centers, 54% involved aircraft in level flight, 26% were climbing, and 20% were descending. These results tend to support (by a few percentage points) Siddiqee's (1973) assumption that most en route conflicts should be in the horizontal dimension.

Schroeder (1982) examined the causes of loss of separation and reviewed the FAA's OE database (SEIS) for the years 1970 through 1980. Errors per million operations in terminal airspace steadily increased during this period. However, the average error rate remained stable for en route airspace. A detailed analysis of the SEIS data for 1977 and 1978 was conducted. As found by Kinney, et al. (1977), most errors occurred under light or moderate workloads. Schroeder (1982) identified an apparent shift in error patterns from 1965 and 1966 when most errors occurred under moderate or heavy workload conditions.

Schroeder (1982) noted, "Thus, while traffic volume and the complexity of the airspace system have increased significantly, a higher percentage of errors involve light to moderate workloads" (p. 261). He also observed that workload levels rated by the controllers did not necessarily depend entirely on traffic density. "There are obviously other aspects of the situation that become involved in the determination of this workload measure other than traffic volume alone" (p. 261). Perhaps these other aspects could be traffic flow or sector characteristic variables.

Kinney, et al. (1977) had found that most errors were attributed to attention, judgment, and communications. However, the recording system changed in 1978, and different error categories were adopted. Most OEs in the 1978 and 1979 data were blamed on a failure of the controller to initiate corrective action. Some errors were caused by omitting to coordinate with other controllers as aircraft crossed sector boundaries. Schroeder (1982) noted: "In fact, a review of error records from 1969 through 1980 indicates that coordination was either a direct or contributing factor in 27.3% to 53.9% of the errors for both en route and terminal airspace" (p. 264). It may be that the controllers were not clear about the current sector configuration in their areas or that sector design created an unacceptable coordination demand. Other important factors were flight data and communication problems. Schroeder's (1982) research suggests that aspects of sector design may affect the way aircraft transition between sectors and create the conditions for OE occurrence.

Two studies on OEs in the Canadian ATC system were conducted by Stager and Hameluck (1990) and Stager, Hameluck, and Jubis (1989). They found that operating irregularities occurred under low to moderate workload conditions with none to normal complexity. Primary error categories included attention, judgment, and communication. Like Kinney, et al. (1977), Stager, et al. (1989) distinguished between direct and contributing causes with regard to controller errors. Direct causes "refer to direct actions or the failure to act on the part of the controller that results inescapably in a loss of separation given a certain system state" (p. 44). Contributing causes "refer to the specific states of the controller (i.e., fatigue, distraction, attitudes, excessive workload, and procedural knowledge) as well as the states of the environment,

including task design" (p. 44). Given these definitions, the focus of this analysis is on contributing factors related to airspace structure and traffic flow characteristics.

Redding (1992) reviewed FAA OE reports and incident statements for 1989 and determined that a failure to maintain situation awareness (SA) was the likely cause of most errors. Errors typically occurred in moderate complexity traffic conditions with eight aircraft under control. Communication and coordination problems accounted for the greatest proportion of errors. The misidentification or misuse of radar data was the attributed cause of 37.6% of total errors. The author recommended that specific instruction and practice in maintaining SA be added to the current ATC training program.

Schroeder and Nye (1993) reviewed the FAA's Operational Error/Deviation (OED) database for the years 1985 through 1988 to examine the relationships between workload (traffic load and complexity) and causal factors. As was found in other studies (Kinney, et al., 1977; Stager and Hameluck, 1990; Stager, et al., 1989), most OEs occurred under average or lower traffic complexity conditions. Schroeder and Nye (1993) found differences in ratings of complexity of the traffic situation under which the OEs occurred across ARTCCs but found it difficult to determine whether these differences had any influence on OE occurrence.

Some relationships were noted among error categories. When the radar display factor was involved in the OE, statistically significant correlations were found with communication and coordination factors, suggesting that these three variables may be associated with OE incidents. Overall, the radar display was involved in 56.8% of OEs. Communication and coordination were cited 29.7% and 29.6% of the time, respectively, while data posting and relief briefing were associated with 20.4% and 4.2% of errors, respectively. The finding of coordination problems in these data is similar to Schroeder's (1982) earlier work in this area.

Rodgers and Nye (1993) conducted a study to relate the severity of OEs to air traffic controller workload, as measured by the number of aircraft being worked and the complexity level at the time of the incident. A specific question was whether more severe errors occurred during periods of high workload. There was also interest in the reported causes associated with errors and whether aircraft flight profile and altitude could be involved. Finally, investigations were conducted to determine the underlying factors leading to severe OEs.

The OED database for the years 1988 through part of 1991 was used for this study. Average traffic load at the time of an OE was 8.8 aircraft. It was found that neither traffic load (workload) nor air traffic complexity was related to the severity of OEs. The authors noted that most OEs occurred when at least one aircraft was in level flight and at least one was descending or ascending. However, most moderately severe errors occurred when both of the concerned aircraft were in level flight. This latter statement echoes Siddiqee's (1973) hypothesis that en route ATC errors should result from a loss of horizontal separation between aircraft at the same level.

Moderately severe errors were most likely to result at flight levels less than or equal to 29,000 ft. Horizontal, but not vertical separation, varied as a function of error severity. Higher horizontal separation was associated with errors where the controller had awareness of the problem. There were no salient factors found to explain the 15 severe OEs found in the data analyzed.

Most of the databases containing reports on OEs do not include an underlying analysis of the factors causing the error. For example, although judgment problems might be cited, it is not certain if this resulted from sector design problems, a poor computer-human interaction (CHI), poor controller training, or other issues. Fowler (1980) reviewed ATC problems from a pilot's point of view and echoed such concerns. He noted that the National Transportation Safety Board typically stopped short of fully examining the human factors problems associated with aviation accidents. He suggested that some errors were symptoms of an underlying system weakness. Some of the human factors issues in the ATC system that relate to the issue of ATC complexity included controller failure to coordinate handoffs, noncompliance with procedures, noncompliance with LOAs, use of inappropriate procedures, and failure of managers to advise controllers of procedure changes. Adverse weather

conditions may result in increased turbulence, icing, and storm activity that effectively reduces the amount of airspace available for flights and may result in runway closings. Fowler (1980) thought that such sector-related factors could contribute to OEs and accidents.

The following two studies used simulation-based experimentation to analyze the factors affecting controller workload and performance. They provide another viewpoint in the search for evidence of the influence of ATC complexity on OEs.

Buckley, DeBaryshe, Hitchner, and Kohn (1983) performed two experiments to assess the feasibility of using dynamic real-time simulation procedures for testing ATC systems. The purpose of the work was "to determine the quality of measurement of system performance and statistical treatment that is possible and appropriate in dynamic simulation of air traffic control systems" (p. 1). The studies identified the important basic dimensions for measuring ATC functions in real-time dynamic simulations. Of interest to the topic of OEs is that the authors addressed the issue of the effect of sector geometry and traffic density on various controller performance measures.

The first experiment examined the effects on performance of two en route sector geometries and three traffic levels ranging from very light to very heavy. Data were collected from two, 1-hour runs for each of 31 controllers. The results of this experiment led the researchers to conduct a less complex experiment using only one of the possible six combinations of conditions of sector and geometry. This second experiment examined the effects of replication and provided a sufficient amount of data to enable the completion of a factor analysis. Twelve, 1-hour runs were conducted using the same sector with the same traffic level for each of 39 controllers.

One of the outcomes of the first experiment was that there was a statistically significant effect of sector geometry and traffic density on almost all of the 10 performance measures. There was also a significant interaction effect between geometry and density. Buckley, et al. (1983) suggested that "Sector [geometry] and [traffic] density are, as expected, important factors in determining the results which will occur in a given experiment, but they interact in a complex way. The nature and extent of this interaction depend upon the measures involved" (p. 73). This research provides evidence that both traffic and sector factors may interact to affect controller performance and, presumably, the possibility of OE events.

Stein (1985) conducted a simulation experiment to determine the relationship between a number of airspace factors and controller workload. Workload was measured by the Air Traffic Workload Input Technique (ATWIT) in which the controller pressed 1 of 10 buttons on a console with 1 representing low workload and 10 representing high workload.

Ten air traffic controllers participated in a series of one-hour simulations. Subjects experienced a low, moderate, or high task load as defined by the number of aircraft in a sector and the clustering of aircraft in a small amount of sector airspace. Controller input to ATWIT was performed once per minute. Stepwise regressions were done using ATWIT scores as a criterion measure. Four variables produced a multiple correlation of R = .85 with the workload measure. These were (in order of entrance into the stepwise multiple regression equation) clustering of aircraft in a small amount of sector airspace, number of hand-offs outbound, total number of flights handled, and number of hand-offs inbound.

The study demonstrated a strong relationship between controller workload and a subset of airspace- and traffic-related variables. In addition, controllers were able to provide real-time workload estimates using the ATWIT without any noticeable decrement in performance. Workload was best predicted through a multivariate combination of airspace variables. The factors listed were used to guide research into error causation at the Atlanta ARTCC.

Grossberg (1989) and Mogford, et al. (1993) conducted research to investigate the factors comprising ATC complexity. Grossberg (1989) found a statistically significant relationship between sector complexity, as defined by FAA Order 7210.46, and the rate of OE incidence at the Chicago ARTCC. The correlation was statistically reliable, but low in magnitude. This provided an impetus for obtaining more information on factors that affect sector complexity.

Ninety-seven controllers rated the degree to which 12 factors contributed to the difficulty or complexity of operations in their particular sector or area of specialization. The complexity factors most frequently cited in the Chicago ARTCC included: control adjustments involved in merging and spacing aircraft, climbing and descending aircraft flight paths, mixture of aircraft types, frequent coordination, and heavy traffic. Sector-related factors, such as large sector airspace and intersecting flight paths, received lower ratings.

Grossberg combined the factors with the four highest ratings to form a complexity index. He found that this index was correlated with the number of OEs found in sectors in the Chicago ARTCC. Data were collected for 21 months in 1987 and 1988. The complexity index was highly correlated ($r = .74$) with frequency of OEs. Correlations between the standard FAA formula and the same OE database correlations were not as high ($r = .44$).

Mogford, et al. (1993) conducted a study to examine the cognitive processes associated with ATC. Controllers from the five specialization areas in the Jacksonville ARTCC participated. The purpose of the research was to identify complexity factors and compare the use of direct (questionnaire and interview) versus indirect (statistical) methods for factor identification.

Direct methods included asking controllers to suggest and then rate complexity factors in terms of how they made sectors more or less difficult to control. Indirect methods involved having controllers make paired comparisons with respect to complexity between maps of sectors in five specialization areas. Multidimensional scaling (MDS) was used to formulate complexity factors by determining whether the arrangement of sectors along each MDS axis corresponded to the increase or decrease in some variable or factor related to complexity.

Thirteen of the 19 total complexity factors were produced by both methods, showing a close correspondence between direct and indirect techniques for determining ATC complexity factors. The 19 variables were regressed over an overall complexity criterion formed by ratings of five Traffic Management Unit staff members who were familiar with all sectors in the ARTCC. The factors of complex aircraft routings, spacing and sequencing for departures and arrivals, and frequency congestion during peak periods formed a significant multiple correlation ($R = .85$) with the overall complexity criterion.

After further analysis, the factor definitions were refined and some redundancies removed. The following 16 unique ATC complexity factors were identified:

1. Number of climbing and descending aircraft.
2. Degree of aircraft mix.
3. Number of intersecting flight paths.
4. Number of multiple functions controller must perform.
5. Number of required procedures controller must perform.
6. Number of military flights.
7. Frequency of contacts (coordination) or interface with other entities.
8. Extent to which controller is affected by airline hubbing.
9. Extent to which controller is affected by weather.
10. Number of complex aircraft routings.
11. Extent to which controller is affected by restricted areas, warning areas, and military operating areas.
12. Size of sector airspace.
13. Requirement for longitudinal sequencing and spacing.
14. Adequacy and reliability of radio and radar coverage.
15. Amount of radio frequency congestion.
16. Average amount of traffic.

Although not specifically addressing sector design issues, recent work by Rodgers and Manning (1995) incorporating SATORI measures into a study of OE occurrence at Atlanta ARTCC is relevant for this review. Data for 12 OEs that occurred between 1992 and 1994 were analyzed using the Performance and Objective Workload Evaluation Research (POWER) system, a subroutine of SATORI. (These are a subset of the data that were the focus of the current research project.) POWER supports the collection of a variety of air traffic and sector measures.

Seventeen minutes of data were collected on each incident, 8½ minutes preceding the error and 8½ minutes during the error interval. Multivariate

analyses of variance (MANOVAs) were calculated for the measures in Table 2. Significant differences between the period preceding the error and the error interval were found for the variables in Table 3.

The results suggest controllers were busier during the error period than the preceding period. The data also show that, although there was greater vertical separation during the error period, aircraft density may have increased, as indicated by increased time within the criterion distance.

Given these results, it is not certain how ATC complexity factors may have been operating in these incidents. However, the findings shown in Table 3 (especially with regard to handoffs) could be consistent with coordination problems, a theme echoed by other authors in this literature review.

3.3 Discussion

Given the preceding review, it is helpful to summarize factors from the literature that are relevant to the relationship between OEs and sector or traffic features, as found in Table 4.

The most relevant observation to make about the above summary is how little research has focused directly on the topic of interest: the relationship of sector characteristics to OE occurrence. The only author who directly addressed this was Grossberg (1989). He found that some sector and traffic characteristics (or ATC complexity factors) were correlated with errors. These included control adjustments to merge and space aircraft, climbing and descending aircraft flight paths, mixture of aircraft types, frequent coordination, and heavy traffic. Even in this author's report, it is difficult to determine exactly which factors were found to be correlated with OEs.

One reason for the absence of work on this topic may be due to the tendency for error-reporting systems to classify errors at a high level without providing for an analysis of causality. A very comprehensive review of the FAA OE database by Kinney, et al. (1977) found that most OEs were attributed to controller attention, judgment, or communication problems. However, it was not feasible, given these error categories, to determine if controller, CHI, or sector design problems were involved. It is impossible to conduct a deeper analysis of such data after the fact; the OE reporting system used at the time of the error defines the bounds of the information available. Other efforts to classify OEs by Schroeder (1982), Stager and Hameluck (1990), Stager, et al. (1989), Redding (1992), Schroeder and Nye (1993), and Rodgers and Nye (1993) have had to deal with similar issues in reviewing OE database information.

Without additional information concerning the percentage of time ATCSs spend controlling traffic under various complexity or workload conditions, it is difficult to determine the primary factors associated with these outcomes. Unfortunately, without normative data, one must settle for a description of the factors associated with operational irregularities. Additionally, the reporting process, including the reporting reliability of the investigators, may affect the extent to which these relationships can be determined.

In spite of these limitations, the data suggest some possibilities about the relationship of ATC complexity factors and OEs. Kinney et al. (1977) observed that 2% of the contributing factors listed in the 1974-76 SEIS reports were listed as problems with procedures. Although this term can be used to describe a variety of activities, it can be interpreted as referring to sector-specific actions the controller is supposed to take with regard to air traffic. However, only a low percentage of contributing factors was associated with this category.

Another suggestion referencing or implying the role of complexity factors is found in Schroeder (1982), who implied that factors apart from traffic volume must contribute to controller workload and, presumably, to OE occurrence. Redding (1992) and Schroeder and Nye (1993) found that coordination and misuse of displayed data accounted for many errors.

Coordination is also a theme among other researchers, such as Arad, et al. (1964), Couluris and Schmidt (1973), Stein (1985), Fowler (1980), Mogford, et al. (1993), and (indirectly) Rodgers and Manning (1995). There may be a strong relationship between OE occurrence and the amount of coordination required between sectors. The frequency of this activity is largely determined by the location of sector boundaries. If sector or facility boundaries are placed near an intersection or area of heavy traffic flow, controller workload and the probability of OEs could be increased.

Several authors noted the likelihood of OEs as a function of phase of flight. Siddiqee (1973) predicted that most OEs would occur as a result of a loss of horizontal separation between aircraft flying at the same altitudes. In partial support of this claim, Kinney, et al. (1977) found that most errors in SEIS data happened in level flight and Rodgers and Nye (1993) observed that moderate errors for 1988-90 OEs usually involved aircraft in level flight. However, Rodgers and Nye (1993) discovered that most errors were between an aircraft in level flight and one that was climbing or descending.

All of the studies that focused on a review of error database information found that OEs occurred under moderate or low workload conditions. Rodgers and Nye (1993) suggested that, theoretically, SA might decrease under high workload conditions. However, given the lower number of high workload OEs, it may be the case that SA is enhanced as workload builds, but decreases (perhaps due to fatigue) as workload subsequently diminishes (as also mentioned by Rodgers and Nye, 1993). Low workload may not foster good controller awareness due to the marginal cognitive arousal level required.

Several of the studies reviewed were either theoretical in nature (Arad, 1964; Schmidt, 1976; Couluris and Schmidt, 1973), were experiments designed to investigate controller workload (Stein, 1985) or performance (Buckley, et al. 1983), or were analytical (Fowler, 1980) but have information applicable to our topic. Arad (1964) developed mathematical models to predict conflicts and used rules of separation, average traffic speed, number of aircraft under control, sector size, and flow organization as variables. Schmidt (1976) took a similar approach and stated that conflicts could be accounted for by flow rate, separation standards, route geometry, aircraft speed, aircraft flow rate, angle of airway intersection, and number of flight levels. Couluris and Schmidt (1973) suggested that controller actions (such as handoffs, coordination, and pointouts) are affected by the existence and shape of sectors. Stein (1985) found that controller workload was related to clustering of aircraft in a small amount of airspace, number of handoffs outbound/inbound, and total number of flights handled. Buckley, et al. (1983) discovered that traffic density and sector geometry interacted to affect controller performance. Fowler (1980) thought that ATC complexity was affected by LOAs and weather.

These variables could be considered as ATC complexity factors in the same vein as those suggested by Grossberg (1989) and Mogford, et al. (1993). When combined together, a substantial list of factors is suggested that can be used in research on ATC complexity, controller workload, and OE occurrence. These variables were used as reference points, or guides, while analyzing the characteristics of Atlanta ARTCC sectors where OEs occurred.

It is worth mentioning the work by Empson (1987) and Langan-Fox and Empson (1985) as a different approach to the previously discussed studies. Rather than reviewing historical data, constructing mathematical models, speculating on causes, or conducting experiments, these authors collected real time data by observing military controllers. They suggested some of the now familiar factors that could affect controller workload, such as airspace structure, procedural demands, and traffic type. However, they discussed another interesting variable in noting that errors might occur more frequently when controllers cannot control their pace of work. It may be worth gathering data on whether sector task load in OE sectors is largely driven by external events or can be modified or time-sequenced by the controller.

Finally, further research on OE occurrence should attempt to explain the findings of Rodgers and Manning (1995). It may be that ATC complexity factors can help account for the observed increases in sector transit time, handoff acceptance latency, vertical separation, and aircraft density and the decrease in handoff acceptance rate associated with operational errors.

3.4 Conclusions from the Literature Review

Although considerable work has been completed to attempt to understand the causes of OEs in en route airspace, much of this research has been limited to using the available information contained in error databases. Unfortunately, this approach restricts the investigator to the data contained in the records and precludes in-depth study of the perceptual, cognitive, or environmental factors originally at play. The development of SATORI has made it possible not only to

recreate OE incidents, but also to collect data on controller activities, sector characteristics, and traffic patterns during the time of the error. It is anticipated that these tools will allow a deeper analysis of the conditions surrounding OE occurrence.

The purpose of this literature review was to locate research relevant to the relationship of sector characteristics and traffic flow to OEs. It was found that little work had been done to directly address this issue, perhaps due to the limitations inherent in the available data. However, there were several studies that made a case for the effect of ATC complexity factors on controller workload or error frequency. In addition, it was possible to generate hypotheses about the types of errors that might occur and factors that could contribute to increases in workload, complexity, and the probability of OEs. These findings were applied while investigating the error data available from the Atlanta ARTCC.

The confirmation that some of the variables identified in this literature search are related to OE occurrence is only the beginning of an effort to identify the relevant human performance issues. Hopefully, further research will permit the development of a human error model that is founded on factual information available from the system. This model should contain hypotheses about how these variables are perceptually and cognitively processed by the air traffic controller to result in an error-prone situation.

4. ANALYSIS OF OE DATA

To more fully investigate the relationship of sector characteristics and traffic flow to OEs, and to explore some of the predictions and assumptions identified in the literature review, sector and OE data from Atlanta ARTCC were analyzed.

Information on sector characteristics was collected using the SATORI OpenCreate application, a questionnaire based on the previous ATC complexity work by Mogford, et al., (1993), and 1995 Atlanta ARTCC facility review data. A set of OE data was compiled from Atlanta ARTCC OE Reports. The following sections specify the variables collected and discuss the results of analyses of these data. The data were divided in two sets, focusing separately on sector and OE characteristics.

Given the exploratory nature of these analyses, results were considered significant if $p < .1$. (Probabilities that rounded to .1 were included.) Frequency count variables were considered to be acceptable for inclusion in parametric tests if they contained sufficient categories and could be assumed to be normally distributed in the population. Measures that had five or less categories were not included and, if it was indicated, were analyzed using non-parametric tests.

4.1 Sector Data

Data were collected on the characteristics of sectors at the Atlanta ARTCC and were obtained from three sources. First, OpenCreate was used to extract details on the following variables for each sector:

1. Number of major airports.
2. Percentage of volume the sector occupies of a cube or other regular geometric shape.[1]
3. Number of shelves in the airspace.
4. Total cubic volume.
5. Number of VORTACs.
6. Number of obstructions.
7. Number of intersections.
8. Miles of victor routes.
9. Miles of jet routes.
10. Miles of other routes.

During a visit to the Atlanta ARTCC, further data were collected on the characteristics of sectors using a questionnaire containing 16 ATC complexity factors (16CF) adapted from Mogford, et al. (1993). One Airspace and Procedures Specialist from each area in the facility rated all of the sectors in his or her area on all 16 variables (using 7-point scales). The total complexity score was calculated by summing the 16 factor ratings for a particular sector.

In addition, the results of the 1995 facility review, consisting of average complexity and density ratings for each sector, were included. The facility average complexity estimate is calculated by facility personnel

[1] Many sectors have a very irregular, three-dimensional shape. This measure helps estimate sector shape complexity by determining how close the sector comes to the shape of a regular geometric object, such as a cube.

during the sector validation conducted each year. This assessment involves estimating the sector complexity using a formula that weights various ATC functions (FAA Order 7210.46). These are the functions and their associated weights (in parentheses): number of departures (5), number of arrivals (4), number of radar vectored arrivals (2), number of en route aircraft requiring control actions (4), number of en route aircraft not requiring control actions (2), number of emergencies (4), number of special flights (3), and number of required coordinations (1). These eight functions are evaluated, weighted, and totaled to derive the sector complexity workload value. The density rating is calculated by averaging traffic volume in each sector over a three day period, representing an Atlanta ARTCC 90th percentile traffic day.

4.2 Operational Error Data

Quality Assurance (QA) personnel at each facility are responsible for gathering data and completing an OE Report in accordance with FAA Order 7210.3 (Facility Operations and Administration). For the purposes of this study, a number of fields from 103 OE reports from Atlanta ARTCC were coded and entered into a data file. Those OEs where more than one sector was involved (13), no final report was available (4), or the error was attributed to an equipment failure (1), were not included in this analysis. This left a sample of 85 OEs, covering a three year period from June 1992 to June 1995. For each error, the following variables were available:

1. Report number.
2. Date.
3. Time.
4. Flight level.
5. How many controllers were charged.
6. Causal factors.
7. Type of sector (ultra high, high, or low).
8. Sector number.
9. Radar or non-radar controller charged.
10. Number of aircraft in the sector.
11. Estimated traffic complexity.[2]
12. Vertical separation.
13. Horizontal separation.
14. Number of controllers working the sector.
15. Whether training was in progress.
16. Number of controllers working (including trainees).
17. Whether the sector was combined with another sector.
18. Whether any positions were combined.
19. Whether another facility was involved.
20. Whether the controller was aware that the error was developing.

4.3 Combined Data Set

To examine sector differences that might have contributed to OE incidence, the sector and OE data were combined. The corresponding sector data were attached to each line of OE data (given that each OE occurred in a specific sector). A result of connecting sector features with OEs was that sector data were counted more than once in some analyses, given that more than one error occurred in many sectors.

4.4 Sector Characteristics

This section reviews the sector data to provide basic information about the characteristics of the Atlanta ARTCC airspace. Selected descriptive information on general characteristics of all sectors in the center is included to provide a basis for the investigation of sector factors that may be associated with OEs.

A histogram of total errors (1992 to 1995) for the 45 sectors in the facility is found in Figure 2. This forms a positively skewed distribution with a mean of 1.9 errors, a standard deviation of 2.1 errors, and a median of 2.0 errors. (Each bar in the histogram represents the count of errors between the value of the preceding category and the value of the labeled category.)

Figure 3 shows the distribution of sectors for size or volume of airspace. The average volume was 30,517.1 cubic miles (cu mi) with a standard deviation of 51,242.6 cu mi and a median of 11,314.0 cu mi. There was a wide range of sector sizes with the smallest

[2] Three measures of ATC complexity for Atlanta ARTCC sectors are used in this report. These include the sum of the 16CF factors, a complexity calculation from the 1995 Annual Review, and the estimated complexity of the traffic situation at the time of an OE.

being 4,695 cu mi and the largest at 212,370 cu mi. A large proportion of sectors were between 5,000 and 15,000 cu mi.

As shown in Figure 4, most sectors were low (0 ft to flight level [FL]230) or high (FL240 to FL340). Nine sectors were ultra high, or FL350 and above.

Average traffic density (as measured during the 1995 facility survey) was 6.1 aircraft, with a standard deviation of 1.7 aircraft and a median of 6.1 aircraft. The distribution of sectors for average traffic density is shown in Figure 5.

A factor analysis using sector variables was completed to explore the underlying structure of sector characteristics.[3] The principal components extraction produced six factors that accounted for 76% of the variance in the measures. Table 5 shows the unrotated factor matrix which was more easily interpreted than the varimax rotation. (Variance accounted for is in the first row of data. Highest variable loadings are in bold type.)

Fifty-six percent of the variance was explained by the first three factors. The first factor appeared to be related to traffic volume and activities associated with managing aircraft. The annual facility review measure, average complexity, was loaded on this factor. Average complexity is based on number of departures, arrivals, en route aircraft, emergencies, special flights and required coordination. Factor 1 also had loadings for climbing/descending traffic, frequency congestion, traffic volume, and other traffic management-related factors. Accordingly, Factor 1 was called "Traffic Activity."

Factor 2 was named "Size" in that it had loadings for cubic volume of airspace, miles of airways, and sector size. Both the objective and subjective measures of sector size were related to this factor. The presence of a negative weighting of aircraft mix implied that a low degree of mix (indicating a predominance of larger, jet aircraft) was associated with larger (and higher) sectors.[4] Miles of airways and sector shelving were also part of this factor.

Factor 3 was concerned with military traffic activity and airspace. It also had a loading for adequacy of radio and radar coverage. Although this third variable did not seem to be directly related to military functions, it may have been conceptually associated with military airspace. Areas that have poor radio and radar coverage, or are controlled by the military, are relatively inaccessible to FAA ATC. Factor 3 was called "Military."

Factor 4 was only concerned with the number of VORTACs and intersections. Factor 5 was not well-defined, in that it only had a loading for percentage of a regular shape (such as a cube) that the sector filled. Factor 6 had the distinction of being associated with average density, the second annual review measure. The fact that this variable was not associated with Factor 1 suggests that it may not actually be measuring traffic activity but some other sector characteristic. There were two variables, average density and number of intersections, that were identified with more than one factor.

4.5 Operational Error Analysis

General OE causality information was extracted from the OE Reports. Then the sector and OE data sets were analyzed to search for any patterns that might help explain OE occurrence.

4.5.1 Operational Error Causal Factors

Each of the 85 OEs was categorized by primary and secondary causal factors at the time of the error. Tables 6 and 7 show the breakdown of primary and secondary causes by number and by sector. (Only 22 errors were assigned secondary causal factors.)

Many of the errors (a total of 70%) were primarily attributed to problems interpreting the radar display. Eighteen percent of the errors were due to communication problems (including transposition, misunderstanding, readback, and acknowledgment). Coordination and data posting accounted for 5% and 6% of the OEs.

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[3] The multivariate procedures used in this study were often based on a relatively low number of cases. It is recognized that a larger data set will be necessary before drawing firm conclusions from such analyses. A correlation table for these variables is in Appendix A.

[4] A one-way analysis of variance determined that there was a significant difference in sector size as a function of altitude level, $F(2, 44) = 34.66$, $p = .000$). Tukey Honestly Significant Difference post hoc tests showed a significant difference between low or high sectors and ultra high sectors, with higher sectors being larger.

Secondary causal factors were largely attributed to communication errors and radar display problems. Table 8 shows a summary of all reported causal factors.[5]

4.5.2 Operational Error Conditions

This section reviews the quantitative OE data, analyzing the circumstances under which errors occurred. Figure 6 shows the distribution of OEs by time of day. It appears that most errors occurred between 0800 and 2000 hours. This probably corresponds with normal traffic flows at the Atlanta ARTCC, although no data were available on overall traffic count over time.

Figure 7 is a distribution of OEs by flight level. There were spikes in the OE count between 15,000 ft and 20,000 ft and again between FL300 and FL350. Figure 8 is another rendition of OE by level, except that it shows the distribution of errors by sector type (low, high, and ultra high).

Figure 9 is a combination of Figures 4 and 8, showing the proportion of sectors and OEs by sector type. It appears that a disproportionately high number of errors occurred in high sectors while fewer than might be expected were recorded in ultra high sectors. A chi square test of these data showed that there were significantly different proportions of errors than would be expected given the number of sectors in each group, $\chi^2(85)=12.43, p = .002$. However, this result might be related to normal traffic flow patterns in each sector type.

Traffic count data at the time of each error are plotted in Figure 10. The distribution of errors by number of aircraft in the sector when separation was lost approximates a normal curve with a mean of 8.0 aircraft and a standard deviation of 2.9 aircraft. When comparing these data with the average density of sector traffic reported in Figure 5, it is evident that traffic density at the time of an error was, on the average, 1.5 aircraft higher.[6] This difference was significant with $t(134.94) = 4.12, p = .000$.

Figure 11 is a plot of OE count by estimated complexity rating (from the OE report). The complexity of the air traffic situation at the time of the OE was assigned after the error occurred on a scale of 1 (low) to 5 (high). Average complexity was 3.4 with a standard deviation of 1.2 and a median of 4.0. Most errors were found in the moderate (3 or 4) range. OE report complexity had low, but significant, correlations with average (annual review) sector complexity ($r = .24, p = .030$) and total 16CF ATC complexity ($r = .40, p = .000$). It had a high correlation with number of aircraft in the sector at the time of the error ($r = .86$, $p = .000$) and low, but significant, correlations with 16CF traffic volume ($r = .24$, $p = .029$) and average (annual review) sector traffic density ($r = .21, p = .052$).

Figure 12 is a plot of OE frequency by workload index. Workload was calculated based on an approach developed by Rodgers and Nye (1993). The index is the sum of the z scores for complexity and traffic count at the time of the error. It takes into account both sector and traffic factors in estimating controller workload. As can be seen in Figure 12, the distribution is somewhat negatively skewed, indicating that workload for many errors was higher than the average for all errors.

Figure 13 is a histogram of OEs by amount of vertical separation. The errors were divided into two groups: below FL290 and FL290 and above, given that there are two separation standards in en route airspace. (Below FL290, 1000 ft is required, while at FL290 and above, 2000 ft is the minimum.) As seen in the graph, two concentrations of separation at closest point of approach were found, corresponding to the two standards. Although there were some errors with less than 1000 ft of separation at the higher levels, most had at least 1000 ft.

Figure 14 depicts the horizontal separation between aircraft pairs at the time of OEs. The distribution is negatively skewed with a mean of 3.6 mi, a standard deviation of 0.9 mi, and a median of 3.8 mi. Most errors occurred with 3 or more miles of horizontal separation remaining.

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[5] The percentage total sums to more than 100 because more than one cause may have been attributed to each error.

[6] The mean of the annual review average density for all sectors was 6.5 aircraft in this calculation. The average traffic density for each sector associated with an error was included, resulting in some sectors being counted more than once in the average. This resulted in a different mean than that computed for Figure 5.

The horizontal and vertical separation data were combined into one separation measure by calculated minimum root mean square (RMS) distance for each OE. Figure 15 shows the RMS distance for OEs that occurred below and above FL290. The mean separation was 21782.8 ft, with a standard deviation of 5641.8 ft and a median of 22841.1 ft.

Figure 16 shows the number of controllers working at the time of the error. One controller, in the radar position, always works the sector. As traffic increases, a second controller in the data position is added. During extremely busy periods, an assistant controller is assigned. As can be seen in the graph, most errors occurred with one or two controllers working. However, this may merely reflect normal staffing patterns.

One of the items contained on the final report prepared after the occurrence of an OE requires an assessment of the involved employee's awareness of the developing error. This item has been on the OE final reporting form for the past 14 years. After listening to the associated voice tape, interviewing the involved controller, and reviewing the error with SATORI, quality assurance (QA) specialists make a determination as to the controller's awareness. Although SATORI simplifies the formulation of this judgment, most QA specialists find the answer relatively easy to ascertain.

Typically, if either the control action to provide separation was not issued in a timely manner, or no control action was initiated, the controller is judged to be unaware of the developing error. However, if the controller actively attempted to provide separation to the involved aircraft, although the control action was either inappropriate or inadequate, the controller is judged to be aware of the developing error. In 73% of the cases in the OE data set, the controller was found to be unaware. Further analysis of OEs with regard to controller SA is found in Section 4.5.4.

4.5.3 Accounting for Error Frequency

One of the primary goals of this project was to determine if sector or traffic characteristics could account for OE incidence. Three techniques based on the general linear model were used to explore these relationships. First, MANOVA was applied to determine if differences existed between sectors with no errors, few errors, or many errors.

In Figure 2, the distribution of errors in the 45 sectors in the Atlanta ARTCC was examined. With a mean of 1.9 errors and a standard deviation of 2.1 errors, it was decided to separate the sectors into OE frequency groups with 0 errors, less than 4 errors (low error sectors), and 4 or more errors (high-error sectors).[7] There were 15, 22, and 8 sectors in each group, respectively.

Bivariate Pearson and Spearman correlations were calculated between 29 variables from Section 4.1 and the sector OE frequency measures (number of OEs and OE frequency group). All correlations significant at the $p < .1$ are listed in Table 9.[8]

The correlation results were used to screen variables for inclusion in the MANOVA, with OE frequency group as the independent variable. Eight variables achieved statistical significance of $p < .05$ or less. These were included in the MANOVA which was significant with Hotellings $F(16, 68) = 1.60$, $p = .094$[9]. Four dependent variables emerged with statistically significant contributions ($p < .05$) to this result. Four other variables were significant at the $p < .1$ level.

Table 10 shows one-way analysis of variance (ANOVA) tests for the eight OpenCreate, 16CF, and facility review data variables that were included in the MANOVA. Results where $p < .05$ indicate statistically significant differences in sector characteristics between error groups are shown in bold print. (There were also several tests significant at the p < .1 level.) Tukey Honestly Significant Difference post hoc tests were performed on the

[7] The division between low and high error sectors was set at one standard deviation from the mean, or at 4.0 errors.

[8] Results at or near the $p = .1$ level were reported in these analyses, given that the emphasis was on data exploration. In this case, a Type I error (incorrect detection of a difference) would only lead to further investigation with a larger data set. A complete Pearson correlation table for the sector variables in Section 4.5 is found in Appendix A. A few of the variables did not meet the assumptions of normality and homoscedasticity, so the results should be interpreted with caution.

[9] Only those variables correlated with $p < .05$ were included in the MANOVAs. This was to control the number of variables in the analysis and to improve the reliability of the outcome.

significant ANOVAs (with $p < .05$). In each instance, the only significant contrasts were between the zero and the high-error sectors.

Number of major airports, although correlated with OE group, was not include in the MANOVA because the variable contained too few categories. It was not possible to conduct a chi square test against OE category because of zero frequency counts in some cells of the contingency table.

Although sector size did not emerge as a discriminator for OE frequency groups in this analysis, a trend noted in the data is worth reporting. Figure 17 shows a graph of sector size as a function of OE group. The variance evident within the no and low-error groups (as represented by the standard deviation error bars) was probably the reason that significant differences were difficult to detect using ANOVA. However, it is clear that the high-error sectors were distinct in having a consistently smaller volume than the zero or low-error sectors. This is supported by a statistically significant t test (in spite of the high variability) between the combined no and low-error groups versus the high-error group, $t(37) = 2.57, p = 014$.

Another analysis of differences between sectors with low and high OE frequencies was conducted to consider relevant OE variables. The difference between this and the preceding analysis is that OE characteristics recorded at the time of the error, as opposed to general sector features, were being considered. The goal was to determine if OEs that occurred in sectors with many errors were different from those taking place in low OE sectors.

Table 11 shows the bivariate Pearson and Spearman correlations (for only those variables where $p < .1$) between sector OE frequency measures (number of OEs and OE frequency groups) and relevant OE variables from Section 4.2.

A MANOVA was not conducted, in that only one variable had a significant correlation of $p < .05$ with OE group. However, the univariate ANOVA for number of aircraft in the sector was significant at $p < .1$, with means larger for the high-error sector group ($M = 7.49$ versus $M = 8.55$). The ANOVA conducted for complexity was significant at $p < .05$. In the low-error group, the mean for complexity was $M = 3.05$ and in the high-error group it was $M = 3.64$. Also, the test involving workload index was significant at $p < .05$, with means larger for the high-error sector group ($M = -.44$ versus $M = .41$).

A chi square test for position combined revealed a significant interaction between low and high-error group and whether the sector was combined with another sector at the time of the error, $\chi^2(1) = 7.13, p = .008$. Positions were combined less frequently in sectors with a high frequency of errors.

Two other techniques, multiple regression and discriminant analysis, were employed to predict OEs using the variables from Section 4.1. The relevant and permissible sector characteristic variables identified in Section 4.1 that had significant correlations with number of errors were submitted, using a stepwise procedure, into a multiple regression analysis with total OEs as the dependent measure. (In this case, Table 9 was not used for screening given that the stepwise procedures screens for the contribution of variables to the analysis.) The results shown in Table 12 suggest that it is possible to explain OE incidence in the Atlanta ARTCC sectors by evaluating frequency congestion and the influence of restricted airspace. The amount of variance in OE incidence accounted for by these two factors was 31%. (With three outliers removed, this increased to 45%, $p = .000$.)

Discriminant analysis was used as an alternative approach for predicting which sectors would have errors. Similar to the MANOVA discussed earlier, it determined how well the relevant and permissible variables in Section 4.1 distinguished between no-error, low-error, and high-error sectors. Discriminant analysis has the advantage of providing success rates for predicting group membership.

All of the applicable and permissible ATC complexity variables were made available for the procedure. Applying a stepwise approach yielded two discriminant functions, with a combined $\chi^2(4) = 18.33, p = .001$. The first function provided most of the discriminating power; the second was not significant when the first was removed. The first function accounted for 33% of the variability in the grouping data. Frequency congestion and the effect of restricted airspace were the only two statistically significant factors entered into the equation ($p < .01$).

When using the resulting equation to predict group membership, there was an overall 58% success rate. Notably, the individual success rates for predicting whether a sector would have low or high OE rates were 68% and 63%, respectively. The formula correctly predicted that a sector would have zero errors for 40% of the cases. The rates of correctly identifying sectors from each group by chance would be 33%, 48%, and 18%, respectively, for the no, low, and high-error groups.

4.5.4 Situation Awareness and Operational Errors

For each of the 85 OEs in the database from Atlanta ARTCC, a QA Specialist had made a rating of the presence or absence of SA. Analyses of the OE and sector data were made to investigate whether controller SA was related to any characteristics of errors or the sectors in which they occurred.

As in Section 4.1.3, Spearman correlations were computed between relevant, OE-related variables from Section 4.2 to screen them for a MANOVA with SA category as the independent variable. The only significant correlation with SA category was for horizontal separation, $r_s = .30$, $p = .005$. A *t*-test for horizontal separation as a function of SA category showed significantly lower separation for errors in the no-SA group, $t(54.69) = -3.06$, $p = .003$ ($M = 3.39$ versus $M = 3.97$). A chi square test showed no significant difference between no-SA and SA groups as a function of sector type (low, high, or ultra high).

Further analyses considered the sector characteristics associated with each error. Therefore, the combined set of sector and OE data was used. The statistical test that addressed sector characteristics as a function of SA had to take into account that more than one OE occurred in many sectors. So if several errors were found in a given sector, that sector's characteristics were weighted more heavily in the analyses than with sectors where there were few errors.

Spearman correlations between sector characteristics in Section 4.1 and SA group (conducted for screening purposes) revealed that only military traffic and military operating areas had low correlations, $r_s = -.19$, $p = .085$ and $r_s = -.19$, $p = .082$, respectively. *t*-tests were conducted and significant differences were found (at $p < .1$) for military traffic, $t(83) = 1.78$, $p = .079$ (no SA, $M = 2.98$ and SA, $M = 2.39$) and for military operating areas, $t(83) = 1.70$, $p = .093$ (no SA, $M = 2.94$ and SA, $M = 2.13$). This indicates that there were few outstanding contrasts in sector measures as a function of SA.

However, when OE frequency with and without SA was plotted against overall sector errors, a trend was evident, as shown in Figure 18. (Sector names and OE totals are shown on the x-axis.) In this analysis, sectors with one error were omitted. (Controllers were always aware in these cases.) It appears that, as the number of errors in sectors increased, there were more errors of which the controller had no SA.

The correlation of overall error count with the number of no-SA errors was $r_s = .83$, $p = .000$ and with SA errors was $r_s = .33$, $p = .130$. For the high SA sectors, the correlation of overall OE count with non-SA errors was $r_s = .86$, $p = .006$ and with SA errors was $r_s = .36$, $p = .386$. These results confirm the trend evident in Figure 18 that error-prone sectors have many errors where there is no awareness of the developing problem. Or, as overall OE rate increases, no-SA error rate rises faster than SA error rate.

Referring to Table 10, there were a number of statistically significant and near significant differences between low and high OE sectors. This suggests that some sector characteristics may negatively affect SA, which in turn leads to higher OE rates.

4.6 Summary and Discussion

The preceding analysis of OE data will be summarized in this section. The results will then be examined in terms of questions and predictions identified in the literature review.

4.6.1 Current Findings

There was an average of two errors per sector at the Atlanta ARTCC during the period (June 1992 to June 1995), with one sector (Burne) having nine errors. The 45 sectors in the facility varied widely in volume, with a median of 11,314 cu mi. Twenty-three sectors were low (0 to FL 230), 13 were high (FL240 to FL340), and 9 were ultra high (FL350 and above). Average traffic density (based on average traffic volume in each sector over a three-day period in the 1995 annual facility review), was 6.1 aircraft per sector.

A factor analysis of 26 of the sector characteristic variables indicated 3 possible underlying dimensions: Traffic Activity, Size, and Military. Three further factors were identified but did not account for much of the original information. However, the annual review measure of average traffic density did not appear to be closely related to other estimates of traffic volume (such as 16CF ratings of frequency congestion and traffic volume), suggesting that it may not be performing as expected.

A review of the OE database for the 85 errors collected between 1992 and 1995 shows that 81% of the overall causal factors were attributed to problems with the radar display, 29% were assigned to communication errors, and 11% to coordination.

OEs at the Atlanta ARTCC during the reporting period mostly took place between 0800 and 2000 hr and concentrations were found between 15,000 and 20,000 ft and between FL300 and FL350. Given that separation standards change at FL290, the flight levels of OEs tended to be distributed into two groups, according to the zone in which they occurred. A disproportionately high number of errors occurred in high sectors, with fewer than expected in ultra high sectors.

Mean traffic volume at the time of an OE was significantly higher than as reported by the 1995 annual review of average sector density. The average density of 8.0 aircraft when an error occurred was nearly one standard deviation above the base rate level of 6.5 aircraft. Judgments of complexity at the time of an OE averaged 3.4 (on a scale of 5), and most errors were rated as occurring in moderately complex conditions. A workload measure derived from the traffic density and complexity data indicated that some errors occurred at above average workload levels, as compared to the whole set of OEs. Normative or baseline workload data for Atlanta ARTCC sectors were not available for comparison.

The minimum horizontal and vertical separation distance at the time of the error were further analyzed by considering RMS distances. Although there are different vertical separation requirements above and below FL290, the 1000 ft of additional separation only creates another 50 ft of straight line distance. Most errors were found to have at least 20,000 ft (or about 3.3 mi) of RMS distance remaining.

Conflict severity was calculated for the OEs and it was found that 84% were moderate and 16% were severe. There was a moderate correlation between sector type (or level) and severity, suggesting that more severe errors occurred in sectors below FL230.

Most OEs happened with one or two controllers working. Without normative information, it is difficult to know the proportion of time that one, two, or three controllers typically work a position. In 73% of the cases, the radar controller was not aware of the developing OE.

Sectors in the Atlanta ARTCC were divided in no-error, low-error, and high-error groups. Bivariate correlations were calculated between most of the 29 original sector characteristic variables and the OE frequency measures (number of OEs and OE group). Fifteen variables had correlations at $p < .1$ with OE group. Given a significant MANOVA, further analyses determined that there were statistically significant differences between the no-error and high-error groups on four sector variables including frequency of problematic weather, radio frequency congestion, total complexity, and average complexity. There were marginally significant differences (indicating possible trends in the data) for amount of climbing/descending traffic, degree of aircraft mix, number of required procedures, and average traffic volume. In general, these results suggested that sectors with high error counts were more complex than those with no errors.

All measures in the ANOVA increased as a function of error count, except for aircraft mix which decreased. A more homogenous (low mix) traffic pattern composed of high-speed jets could pose more challenges for maintaining separation.

While sector size (as measured by OpenCreate) did not emerge as a significant variable in the ANOVAs, inspection of the size differences between OE frequency groups showed a relationship, and this was supported by a statistical test. It is clear that high-error sectors were only about 32% of the size of no- and low-error sectors. More errors occurred in lower, smaller sectors. It is not surprising that smaller sector size would induce more complexity.

ANOVAs were used to consider the differences in OE characteristics between low and high OE sectors. First, correlations were found between OE group (low

or high) and number of aircraft in the sector (at the time of the error), complexity (as rated at the time of the error), workload index, and whether the position was combined at the time of the error. It was found that the high-error sectors had more aircraft, were more complex, and had higher workload. High-error sectors were also less likely to have positions combined than the low sectors.

Several approaches were used to attempt to predict OE occurrence from sector and traffic variables. Using multiple regression, it was possible to account for 31% of the variance in the total sector errors using the sector characteristics of radio frequency congestion and effects of restricted areas. A discriminant analysis using frequency congestion and the effect of restricted areas resulted in a formula that was able to classify sectors into error frequency groups with 58% average accuracy.

OEs were separated into those where the primary controller had awareness of the developing problem, as opposed to those where no awareness was present. The only OE characteristic that was significantly different between SA error groups was horizontal separation which was greater when SA was present.

Using sector variables, significant differences were found between SA and no-SA OEs for amount of military traffic and the effect of military operating areas, with no-SA OEs tending to occur with more of each. As the frequency of errors within individual sectors increased, there was evidence that SA diminished. In high-error sectors, there was a general reduction in awareness of errors. Thus, those sector characteristics listed previously that discriminated between low- and high-error sectors also probably have a relationship to SA.

1.6.2 Relationships to Previous Research

The literature review identified many factors possibly related to OE or conflict occurrence. Table 4 has been reproduced in Table 13 to list the findings from this study that address the issues raised in the literature review. (NS indicates no statistically significant results.)

Although it was possible to summarize the primary and secondary causes attributed to operational errors in the 1992 to 1995 data, the rating system had changed so that direct comparisons to Kinney, et al. (1977), Stager and Hameluck (1990), and Stager, et al. (1989) were not feasible. However, Schroeder (1982) noted that coordination was cited as a contributing factor in 27 to 54% of the OE reports between 1969 and 1980. Redding (1992) apparently used the more recent classification system and found that misidentification or misuse of radar data was cited in 38% of the 1989 error reports. Schroeder and Nye (1993) employed the same categories for 1985 to 1988 data. Table 14 shows a comparison of the Schroeder and Nye (1992) results with the 1992 to 1995 data.

A larger proportion of errors in the current study were attributed to problems with the radar display than in previous reviews. Communication problems remained about the same as in the Schroeder and Nye (1993) report, but fewer errors were assigned to problems with coordination or data posting.

Many factors were suggested in the literature review as being possibly related to OEs (Arad, 1964; Schmidt, 1976; Couluris and Schmidt, 1973; Stein, 1985; Buckley, et al. 1983; Fowler, 1980; Grossberg, 1989; Mogford, et al., 1993; Empson, 1987; Langan-Fox and Empson, 1985). These are listed in Table 13. The variables in the current study that were found to be correlated with OE rate or that distinguished between high and low OE sectors are linked, where possible, to the specific issues raised in the literature review. In many cases, there is some correspondence, indicating that some of the findings from the current research directly support (or in some cases fail to corroborate) previous work in this area.

Several studies noted that most OEs occur during times of moderate workload or traffic volume (Kinney, et al., 1977; Schroeder, 1982; Stager and Hameluck (1989, 1990); Redding (1992); Schroeder and Nye, 1993.) While no direct ratings of workload were available for the current set of errors, there were indications that errors occurred under higher than normal traffic densities. The average traffic load at the time of an OE was eight aircraft, the same number found by Redding (1992). Rodgers and Nye (1993) found that the average traffic load for 1988 to 1991 OEs was 8.8 aircraft. However, indirect corroboration of the findings regarding moderate workload were found in the complexity ratings given each OE.

The average complexity was 3.4 (out of 5), and most errors were in the moderate range. When a derived workload measure was calculated, it appeared that OEs occurring in high-error sectors had marginally higher workload.

Although several authors suggested that coordination could be a factor in OE incidence (Arad, et al., 1964; Couluris and Schmidt, 1973; Stein, 1985; Fowler, 1980; Mogford, et al., 1993; Rodgers and Manning, 1995), there was not much evidence in the current data set to support this hypothesis. The only measure of the amount of coordination required in a sector was one item on the 16CF, and this variable was not correlated with OE frequency nor did it discriminate between groups of sectors with different OE severities. As noted earlier, coordination was mentioned as a factor in OE occurrence in 11% of the reports during the period. However, as a whole, the data do not add much to our understanding about the effects of sector boundary placement and coordination on OE occurrence.

In the literature review, some reports indicated that conflicts usually occurred between aircraft in level flight (Siddiqee, 1973; Kinney, et al. 1977). Rodgers and Nye (1993) found that most errors involved one aircraft in level flight, and one that was climbing or descending, though most moderately severe errors involved aircraft in level flight. The OE data reviewed in this report did not contain information relevant to this topic. However, there was a low, but significant correlation between number of OEs and amount of climbing and descending traffic. This suggests that transitioning traffic had some role in error generation.

Rodgers and Nye (1993) also found that 30% of the 1053 errors they analyzed were rated as moderate in severity while 70% were minor errors. In comparison, the current data show 16% moderate and 84% minor errors, with a much smaller set of 85 errors.

Finally, there is unfortunately not much relationship between the approach used in this research and the recent work by Rodgers and Manning (1995). Aircraft density was generally higher at the time of an OE, but it was not possible to address the other variables used in this previous study, given the data at hand.

5. CONCLUSIONS

Several useful and important findings emerged as a result of analyzing the 1992 to 1995 operational error (OE) reports and investigating relationships between sector and traffic factors and OEs. These will be discussed in this section and recommendations for further study will be enumerated.

Using a combination of OpenCreate and other data, it was possible to generate useful statistics regarding Atlanta Air Route Traffic Control Center (ARTCC) sector features. Of note was the wide range in sector size. These descriptive data may be useful for comparing en route facilities during future research efforts.

Without normative data on the daily traffic flows and typical altitudes, it is difficult to determine whether OE frequency departed from expected proportions, as determined by normal traffic density patterns. It may also be that ultra-high sectors are often combined with high sectors. However, it appears that more OEs occurred in high sectors, and fewer in ultra-high sectors, than would be anticipated, based on sector counts. Future research should gather facility baseline data to support such comparisons.

It is evident that errors tended to occur at above 1995 average traffic density. However, it is again difficult to know how much busier these sectors were relative to normal ranges of traffic density at the time of OEs. As found by Kinney, et al. (1977) and others, the traffic noted in the OE reports may fall within the moderate range. Further data from the Atlanta ARTCC would help determine whether OE frequency departed from expected proportions, as determined by normal traffic density patterns.

OE complexity rating (from the OE report) had a high correlation with aircraft density in the sector at the time of the OE. It had much lower correlations with other general sector volume and complexity ratings. This suggests that more immediate factors, such as traffic density during the OE period, are important in this rating, as compared to overall sector characteristics.

Of interest was the moderate correlation of error severity and sector type (L, H, or UH), indicating that sectors under FL230 tend to have more severe errors.

This result is nearly identical to a finding by Rodgers and Nye (1993) that more severe errors occurred below FL290.

A factor analysis using OpenCreate and sixteen complexity factor (16CF) variables indicated three primary underlying dimensions: Traffic Activity, Size, and Military. The other three factors in the analysis showed no strong patterns, with one factor lacking any distinct loadings. It is reassuring to observe that the average complexity facility review measure was associated with other Traffic Activity variables and that the sector size variables, as measured by OpenCreate and 16CF, were related. However, the facility review traffic density variable was not loaded on the same factor as other traffic density indicators. This suggests that it may lack concurrent validity. Fortunately, all other volume-related measures were loaded on the Traffic Activity factor. It would be helpful to evaluate traffic density in the Atlanta ARTCC sectors in additional ways to better define the nature of the average density measure.

Traffic mix was associated with the Size factor, rather than with Traffic Activity. The presence of a negative weighting of aircraft mix on this factor suggests that a preponderance of larger jet aircraft may be associated with larger sectors. The collection of data on aircraft type for each OE would be useful in this analysis. Adequacy of radio/radar coverage fell in with the Military factor. Areas that have poor radio and radar coverage have some similarity to military airspace in that they are less accessible to FAA air traffic control. Finally, the sector shape measure, percent of cube, seemed to have no relationship to other measures. This could indicate that it taps some independent factor. However, by accounting for only 7% of the variance in the data set, it may be of limited importance.

The potential for a reduction in sector measures to a set of three or four factors holds promise in that it might simplify the process of evaluating sector characteristics. The practice would be to use one or more of the variables that were loaded on each distinct factor. However, given that these variables do not fully represent each factor, some information is lost. Further research would be needed to determine the utility of this approach.

A theoretical issue worth noting is that, given the wide range of ATC complexity measures available, there appear to be only three general characteristics of sectors related to traffic activity, size, and military operations. This makes intuitive and practical sense, given controllers' descriptions of sector workload issues. The level of difficulty of an air traffic situation is often described as an interaction between sector size and the amount and behavior of traffic. This relationship was also found in the Buckley et al. (1983) work where sector geometry and traffic density interacted to affect controller performance.

Stein's (1985) research showed that variables related to the traffic activity and size factors accounted for a large proportion of controller workload. In the current study, Military was discovered to be an additional independent factor. This seems reasonable in that military aircraft and their associated airspace reservations are controlled by outside agents and must be accommodated by the controller in different ways than are commercial aircraft, weather, and other centers.

An application of the factor analysis findings could be used as a general guideline for traffic management systems. Aircraft activity, sector size, and military operations should be included in any formula that seeks to account for or predict ATC complexity.

When comparing sectors with no errors, less than three errors, and four or more errors, there was consistent evidence supporting the role of ATC complexity. First, 15 of the sector and traffic-related variables were correlated with OE frequency or OE frequency group.[10] Also, it was found that there were differences between OE frequency groups on a number of measures. Five variables (including sector size) showed statistically significant differences between groups, and two of these were general complexity measures. Three other variables demonstrated trends in the same direction (increasing errors with higher complexity). This demonstrates a definite role for ATC complexity in OE analysis.

[10] Although many of the correlations found were in the .30 range, and therefore not particularly strong, many were statistically significant. Correlations in this range are acceptable for this type of exploratory research.

It is also interesting to note that three of the variables that were statistically significant, and all four of the marginal variables were part of the Traffic Activity factor. Thus, this factor alone may account for many of the effects that contribute to OE occurrence.

One of the potential benefits of collecting data on factors that might be related to OE occurrence is that the ability to predict these events could improve. This, in turn, would pave the way for the development of practical tools for conflict management that might be used in en route ATC operations. Several techniques were applied to explore this possibility, all using the same underlying statistical approach.

Multiple regression, which was used to build the optimal mathematical combination of variables that will predict the number of OEs in a given sector, accounted for about 31 percent of the available information. The size of this correlation is respectable on theoretical grounds in that it demonstrates that there is a firm relationship between sector characteristics and OE rate. However, it is not of much practical importance in that the equation, in its present form, will not permit accurate conflict prediction.

The fact that only two variables (frequency congestion and restricted areas) entered the regression analysis suggests that there may be a significant amount of redundant information in the data set. (This can been seen in the correlations in Appendix A.) It is interesting to note that one of these variables, frequency congestion, also appeared in the multiple correlation with overall ATC complexity derived by Mogford, et al. (1993). The two variables were members of the Traffic Activity and Military factors, respectively.

Although the regression analysis ultimately employed only two variables, this does not necessarily imply that these are the only meaningful factors for further study. The other sector characteristics also have useful information, but their inter-correlations suggest that there may be only a few underlying themes, as demonstrated in the factor analysis. If description of sectors is the goal, these variables should be retained, for they provide a richness of detail. For predictive purposes, however, it may be adequate to employ a subset of the original measures.

Discriminant analysis was applied in an attempt to use the available variables to predict whether a sector belonged to the no, low, or high-error groups. Using the original measures, frequency congestion and restricted areas again emerged as the only two emergent factors, and it was possible to achieve an average classification accuracy rate of 58%. This resulted in a success rate of 40%, 68%, and 63% for the no-, low-, and high-error groups, respectively. The chance rates of correctly identifying sectors from each group would be 33%, 48%, and 18%, respectively, for the no-, low-, and high-error groups. Thus, the discriminant analysis adds predictive power, especially for identifying potential high-error sectors.

Practically speaking, the approach reflected in correlation or multiple regression might be the most useful in ATC operations. The results of such analyses would indicate that OEs would be more likely to occur with the increase or decrease in certain dynamic sector or traffic-related factors. Such information might assist flow controllers and area supervisors in taking steps to avoid problems before they develop. Another application could be to assist with defining such free flight concepts as dynamic density and flexible resectorization.

There were also static measures, such as sector size, that contributed toward high error frequency. However, from experience, facility personnel already are familiar with which sectors are error-prone. Being able to group sectors by error frequency, as predicted by a set of sector and traffic measures, might be more useful for airspace reconfiguration projects. Another application could be to assist with dynamic resectorization, a concept proposed for free flight.

It would be desirable to determine when high-risk situations are developing and predict potentially problematic sectors. Using information on sector characteristics, the methods used here show some promise, but are not as yet sufficiently powerful. The 16CF questionnaire needs further validation to ensure that it is performing as intended. Some evidence of concurrent validity for some of the items was found in the factor analysis. It would be interesting to create some additional complexity questionnaire items for evaluation

and add variables to OpenCreate. Based on the literature review, some candidate measures might be: a count of airway crossings of sector boundaries (to evaluate coordination requirements), aircraft speeds at the time of the OE, route complexity, a count of event- versus controller-driven activity (Langan-Fox and Empson, 1985), and flight stage (climbing, descending, or level) at the time of the OE. The characteristics inherent in the dimensions of the factor analysis could also be melded into more global questions.

Collection of additional ratings of ATC complexity from Atlanta Center might help stabilize the 16CF data. (Only one controller from each area was used in this study.) Given that previous research found that interrater reliability between controllers from the same areas tended to be only moderate, further steps should be taken to ensure clear definition of each factor, perhaps using graphics combined with written descriptions. A computerized version of the 16CF questions may be worth exploring.

To summarize, this research has shown that high-OE sectors are characterized by problematic weather, radio frequency congestion, high total 16CF complexity, high annual review average complexity, and small size. There is also evidence that these sectors tend to have more climbing/descending traffic, a uniform aircraft mix, frequent required procedures, and higher traffic volume. The general dimensions that describe sector and traffic characteristics are traffic activity, size, and military. Finally, there is limited evidence that OE probability can be predicted using a subset of these variables.

The separate analysis of controller situational awareness (SA) during the development of OEs is important in that, in these data, 73% of the controllers were not aware of the developing error. Presumably, awareness would have prevented many of these errors from occurring, as suggested by Redding (1992). The only sector or traffic characteristic that was clearly different between not aware and aware OE groups was horizontal separation, as found by Rodgers and Nye (1993). However, this result may have been due to the fact that, without awareness, the error was more fully advanced before controller intervention occurred.

It was found that high-error sectors tended to have more no-SA errors. It may be that the presence of awareness of a developing error is a mediating factor controlling the frequency and severity of errors in a given sector. If sector or traffic characteristics tend to somehow interfere with general controller SA, it can be expected that more errors will occur, and they will often be rated as no-SA OEs. Thus, higher ATC complexity may result in the kind of high cognitive loading that contributes to a reduction in SA and leads to an elevated probability of error.

Although direct comparisons between the current findings and previous research in this area were not always possible, there were many links. It was also notable that there was a 24% rise in the attribution of OE causation to problems with the radar display. Coordination and data posting were cited less frequently, and communication remained at about 30%. This represents a significant increase in problems with misreading or misusing visually-displayed data with the concomitant negative impact on SA. A more detailed analysis of this finding is indicated. Changes to information display methods may be required to eliminate some of the causes of these errors.

This project has resulted in a review of the sector- and traffic-related factors associated with OEs. Armed with OE data from the Atlanta ARTCC from a variety of sources (including SATORI), it has been possible to explore relationships between a range of ATC complexity measures and errors. Although this study must be considered as exploratory, it has succeeding in demonstrating a role for sector complexity, as measured by an array of variables, in OE incidence. It has also confirmed the Rodgers and Nye (1993) assertion that SA may be an important mediating factor in the creation and eventual severity of errors. With a larger data set and refined measurement techniques, it may be possible to generate reliable, statistically sound rules for the prediction of OEs, and useful guidelines for sector reconfiguration and design. This could provide direct benefits for the development of procedures and automation tools for reducing errors and enhancing safety in the NAS.

FIGURES

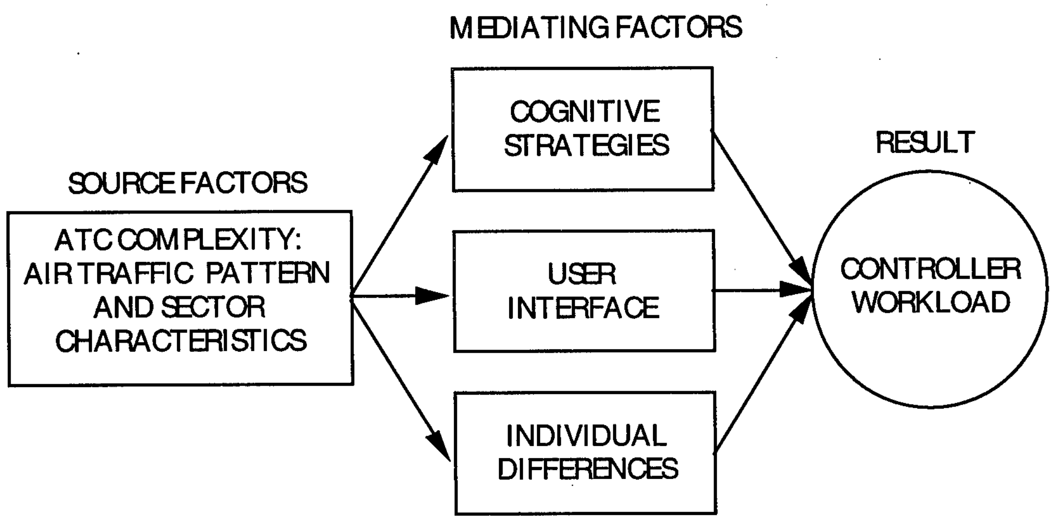

FIGURE 1. FACTORS AFFECTING CONTROLLER WORKLOAD

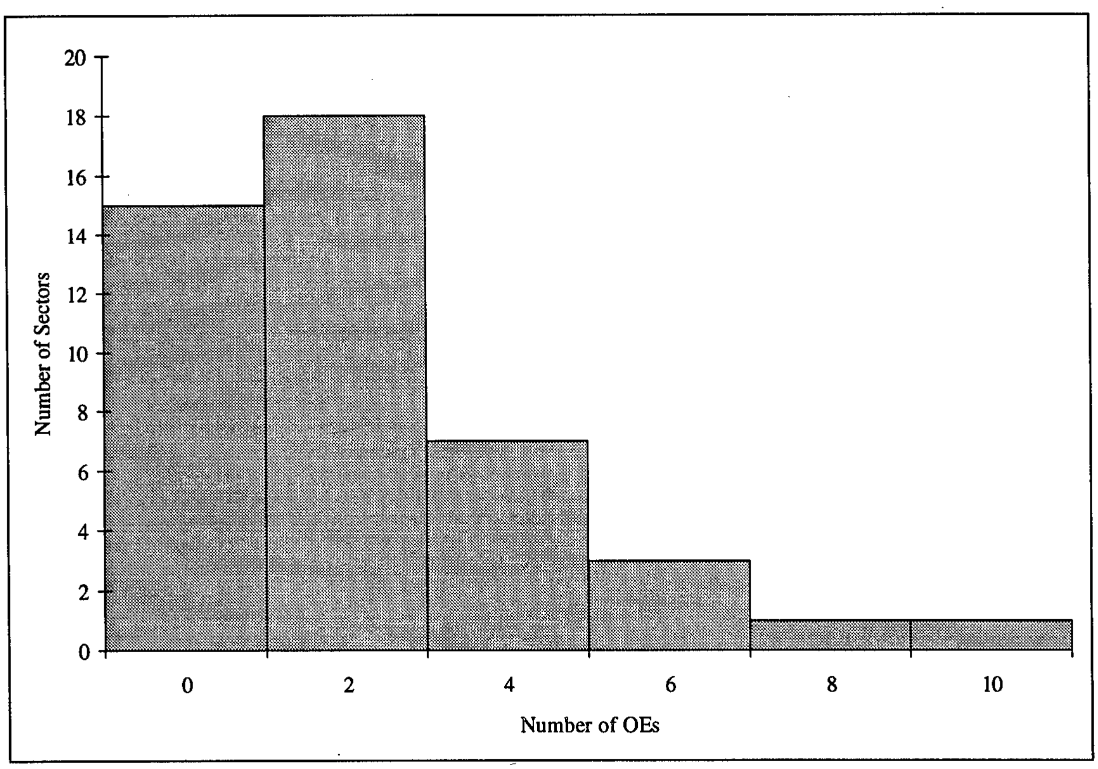

FIGURE 2. DISTRIBUTION OF SECTORS BY NUMBER OF OEs

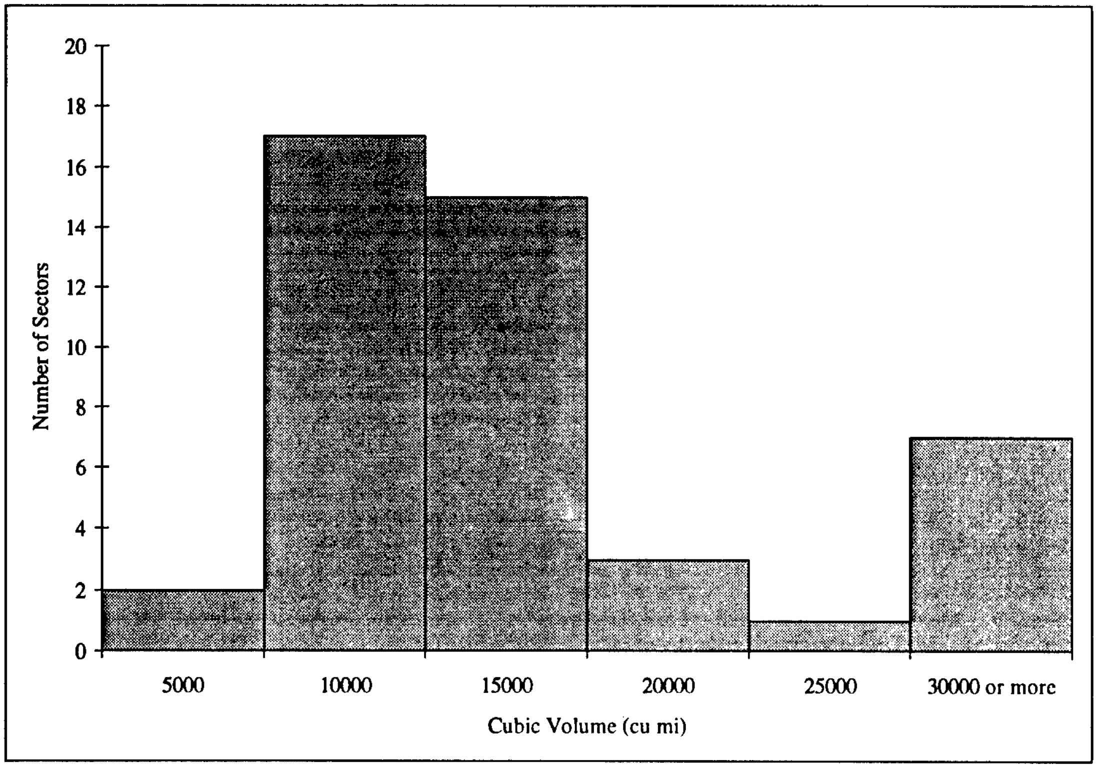

FIGURE 3. DISTRIBUTION OF SECTORS BY CUBIC VOLUME OF AIRSPACE

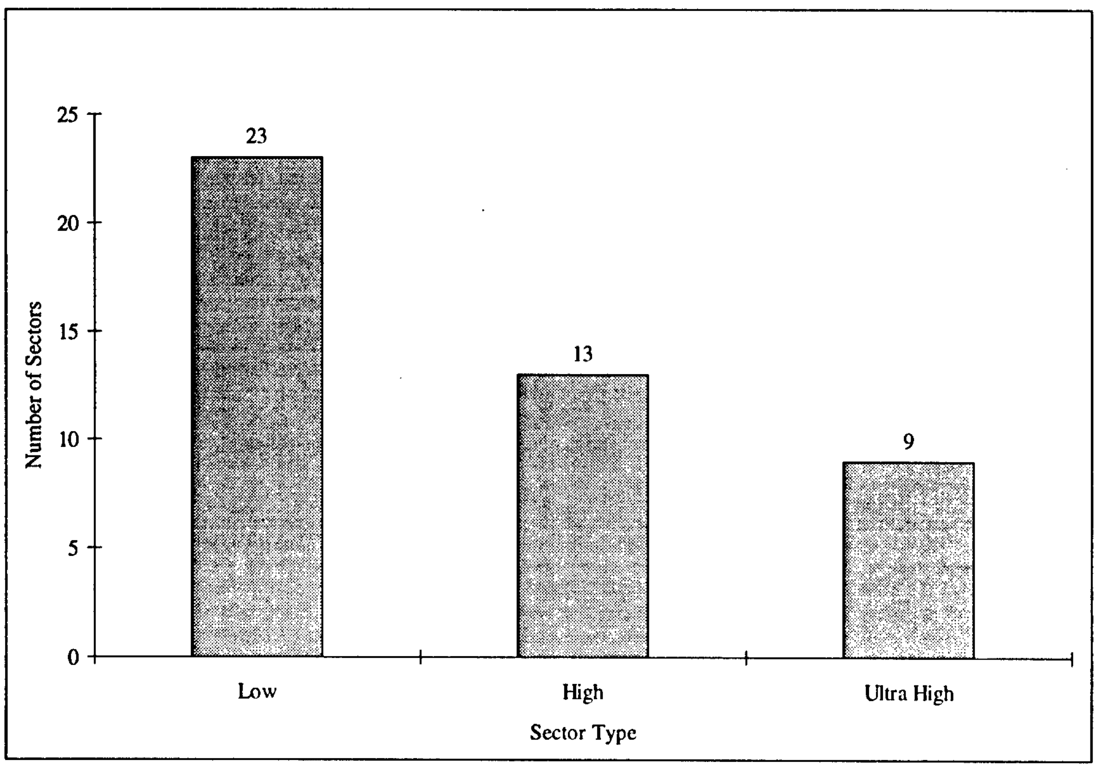

FIGURE 4. DISTRIBUTION OF SECTORS BY TYPE

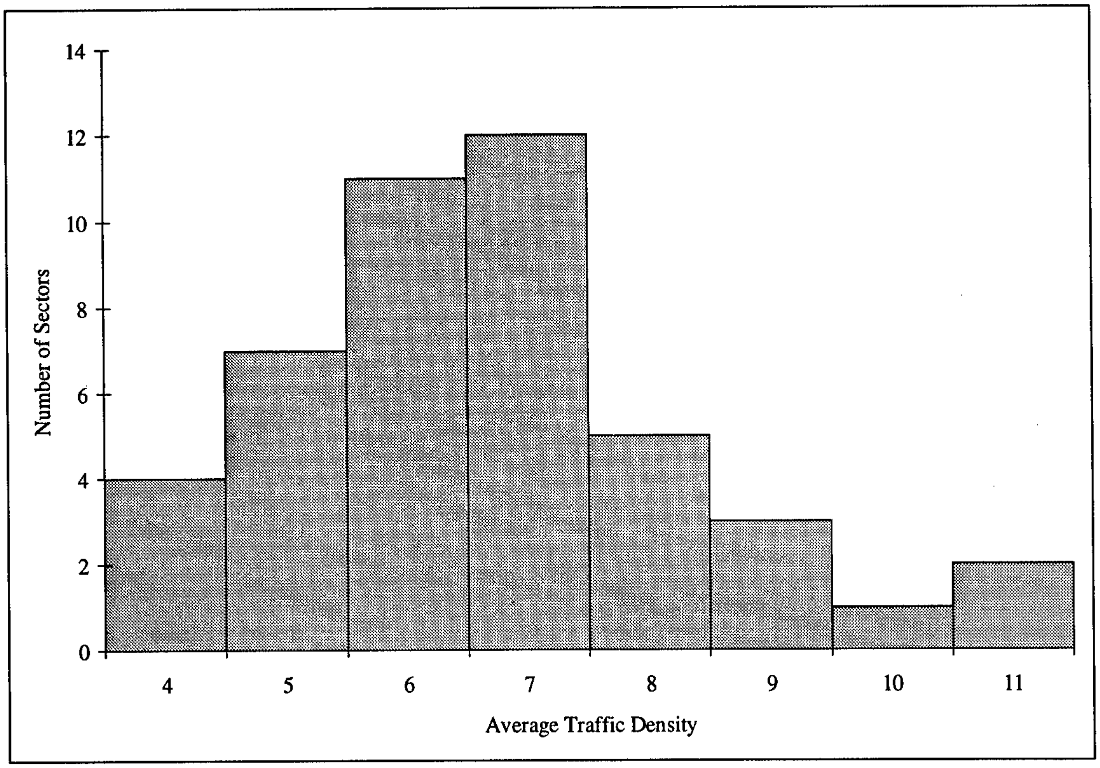

FIGURE 5. DISTRIBUTION OF SECTORS BY AVERAGE TRAFFIC DENSITY

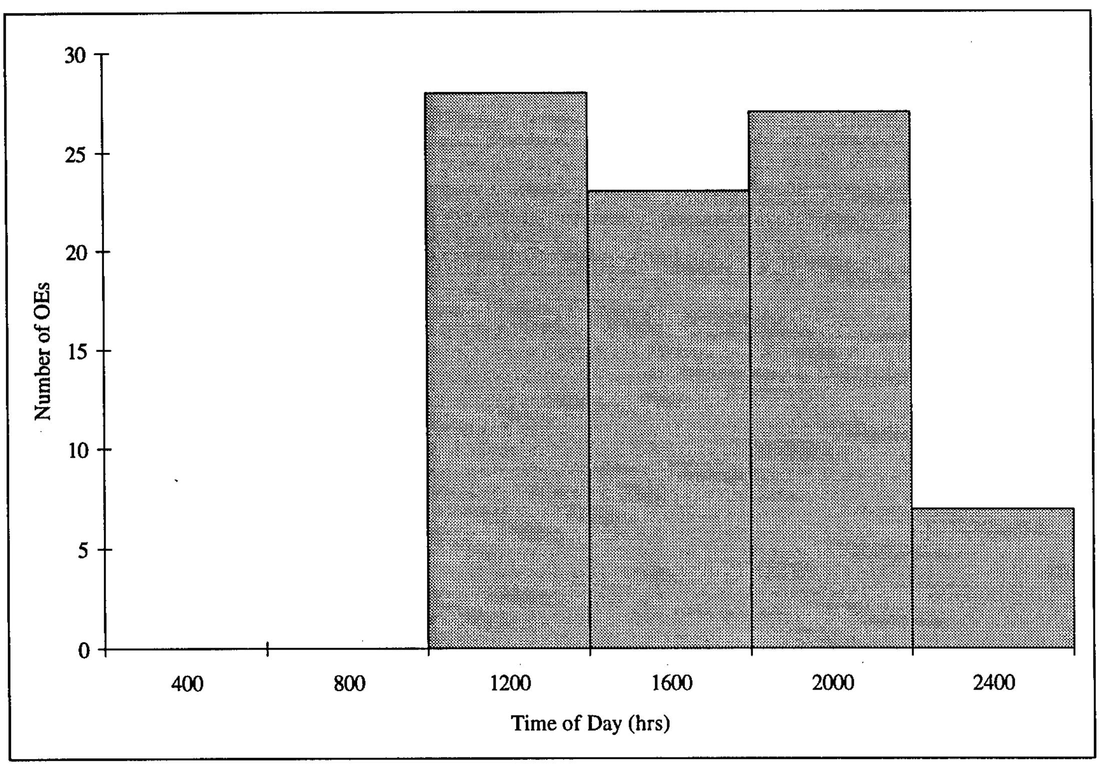

FIGURE 6. HISTOGRAM OF OE COUNT BY TIME OF DAY

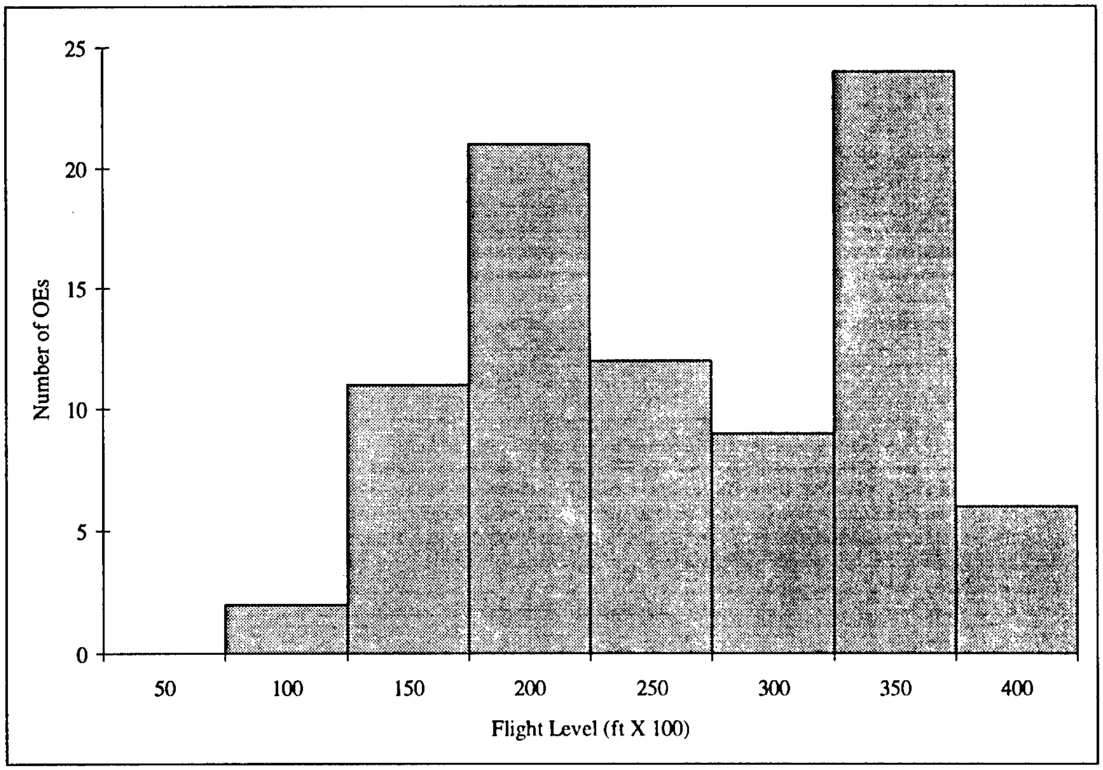

FIGURE 7. DISTRIBUTION OF OEs BY FLIGHT LEVEL

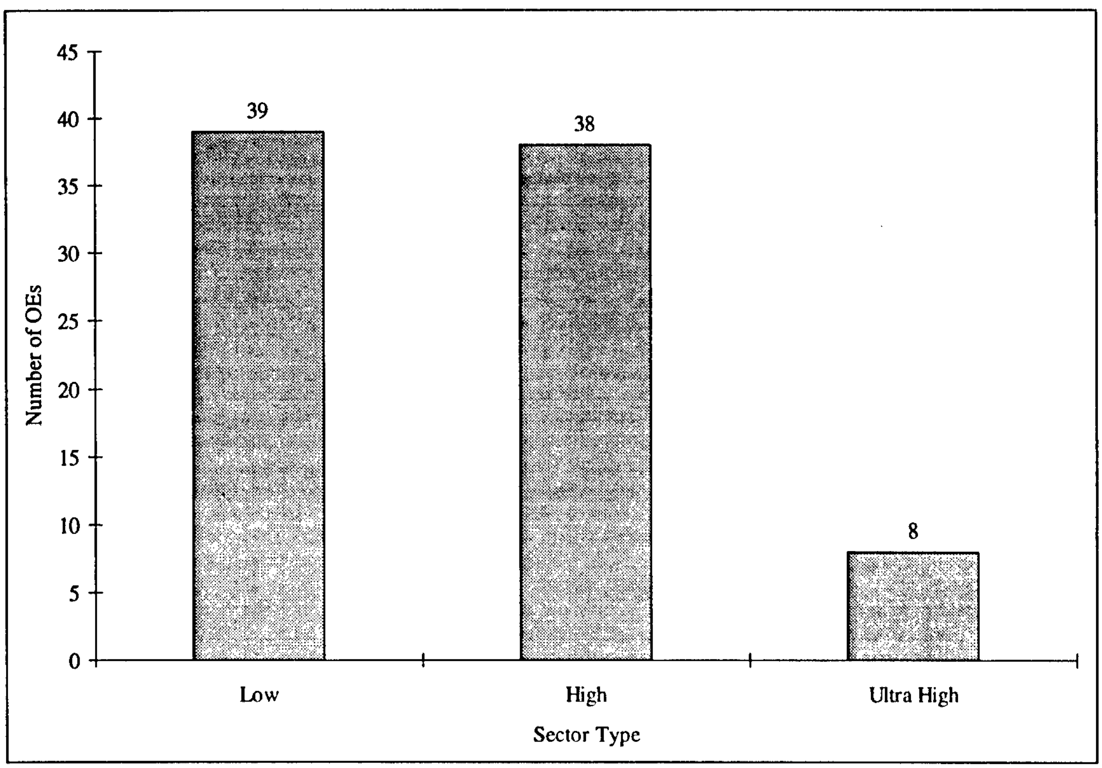

FIGURE 8. DISTRIBUTION OF OEs BY SECTOR TYPE

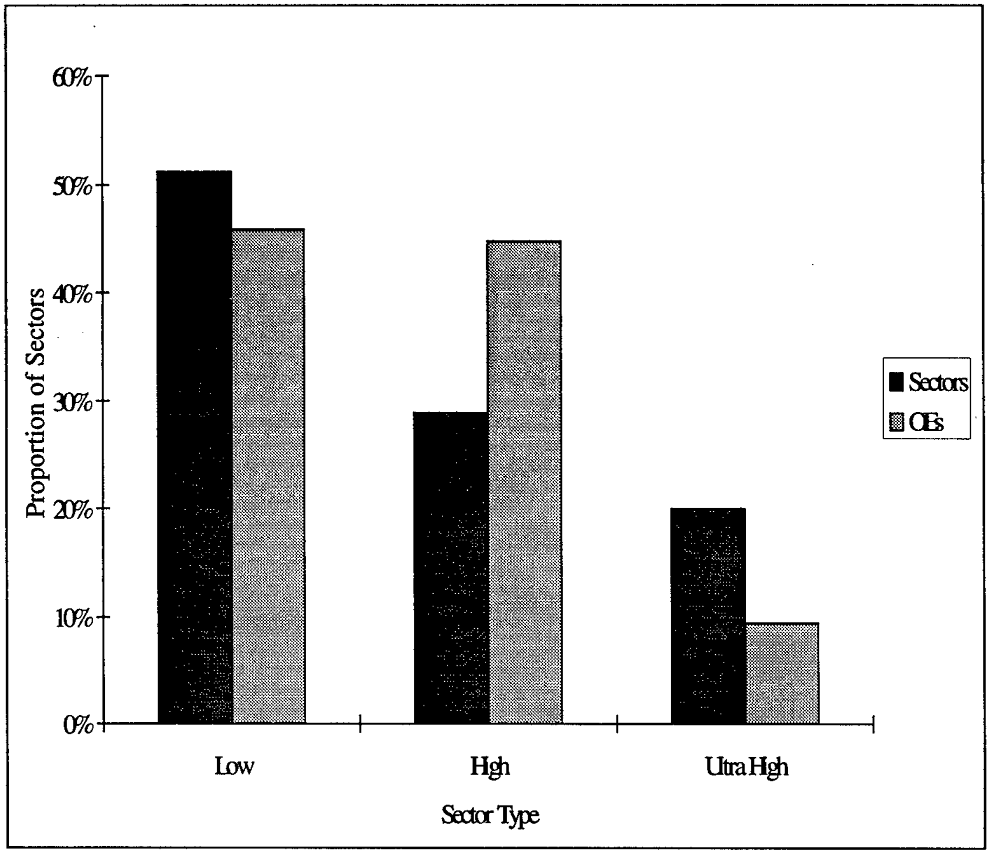

FIGURE 9. PROPORTION OF SECTORS AND OEs BY SECTOR TYPE

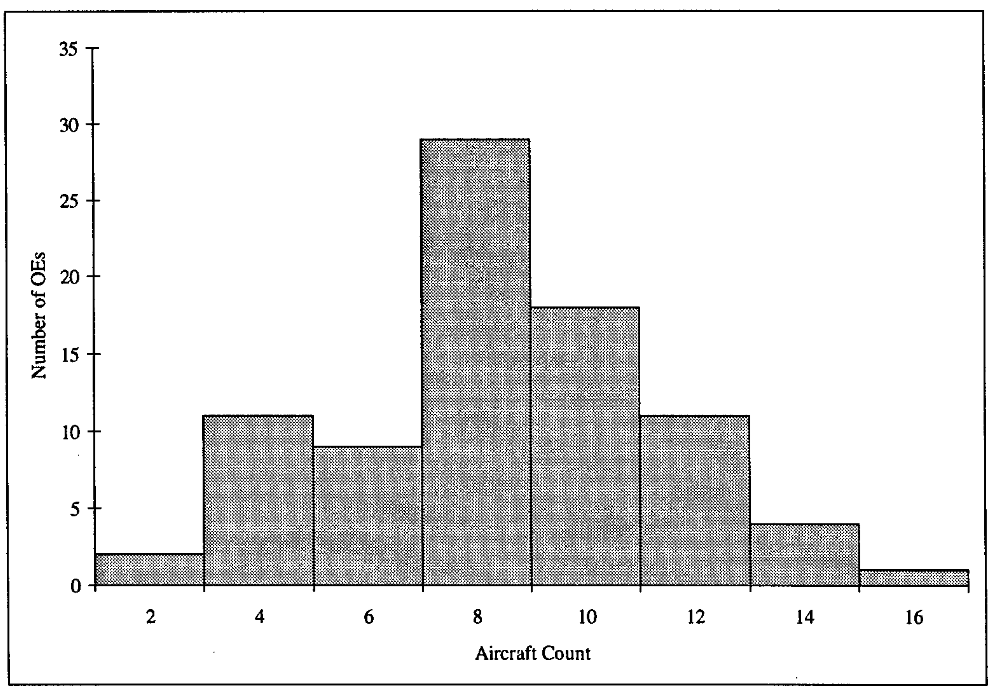

FIGURE 10. DISTRIBUTION OF OEs BY TRAFFIC COUNT

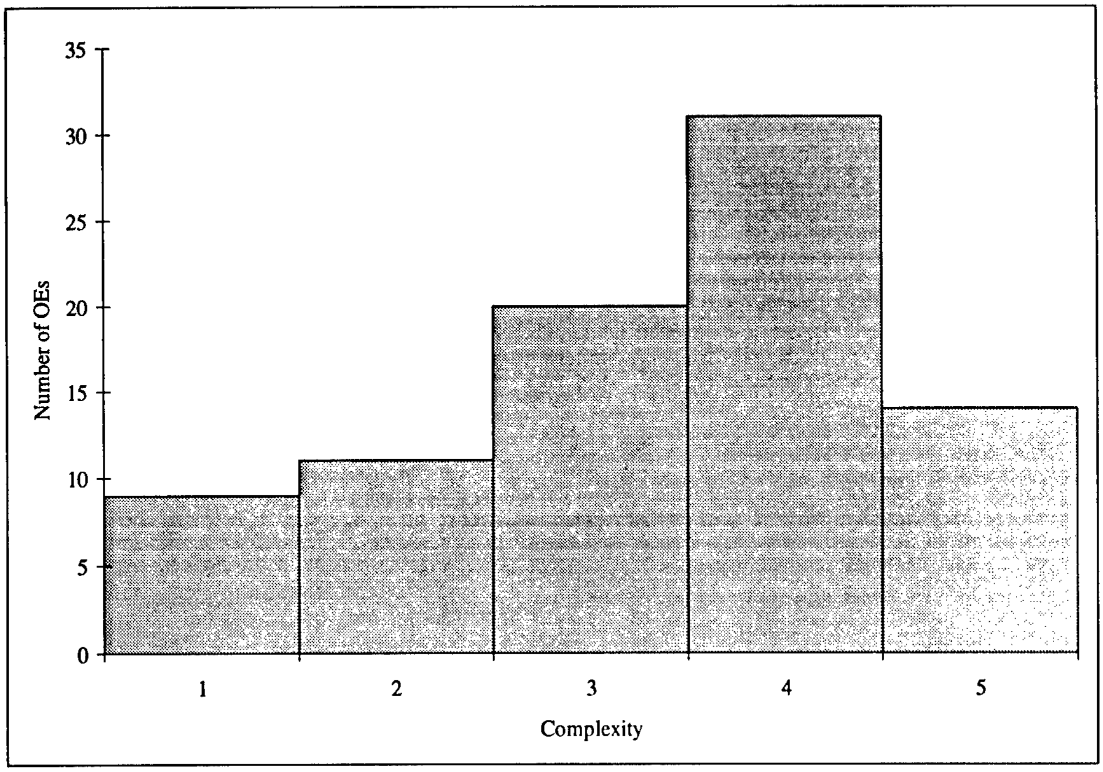

FIGURE 11. DISTRIBUTION OF OEs BY COMPLEXITY RATING

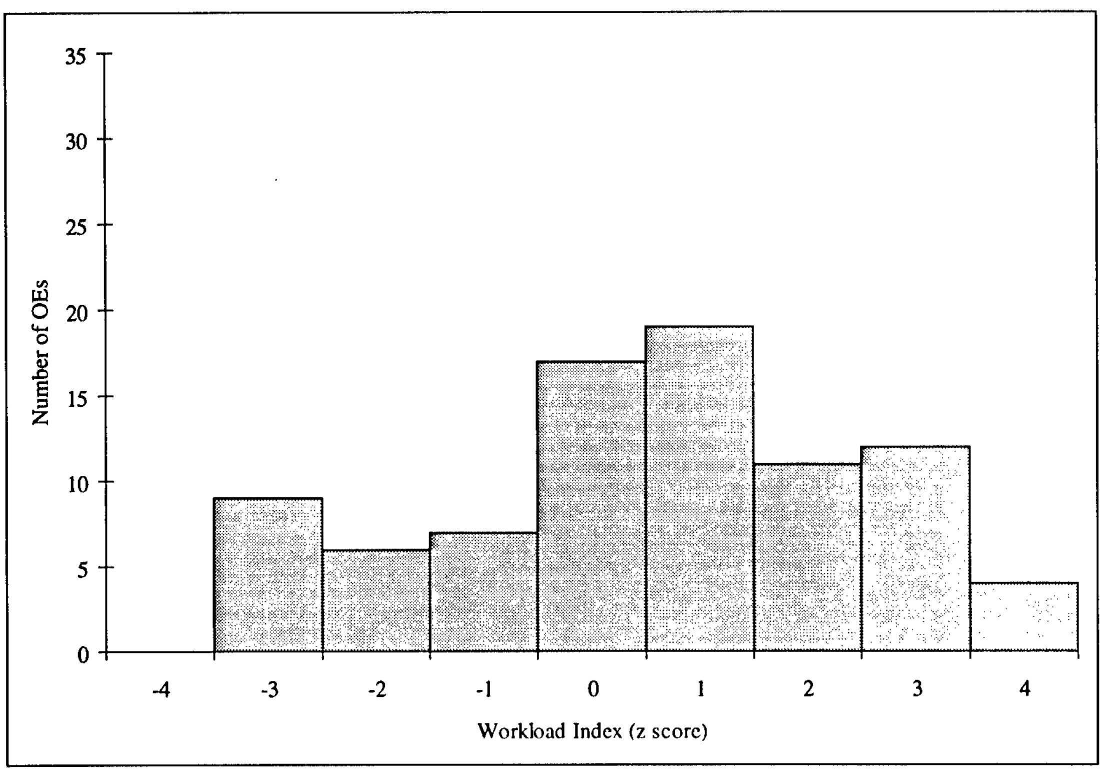

FIGURE 12. DISTRIBUTION OF OEs BY WORKLOAD INDEX

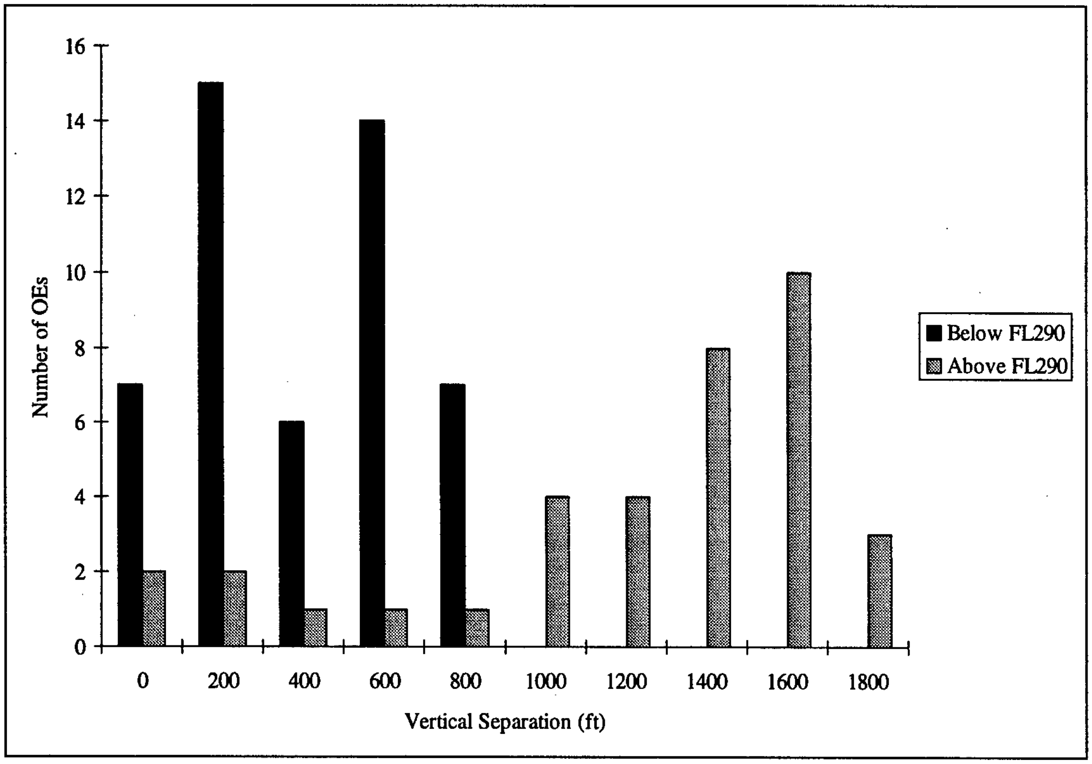

FIGURE 13. DISTRIBUTION OF OEs BY VERTICAL SEPARATION

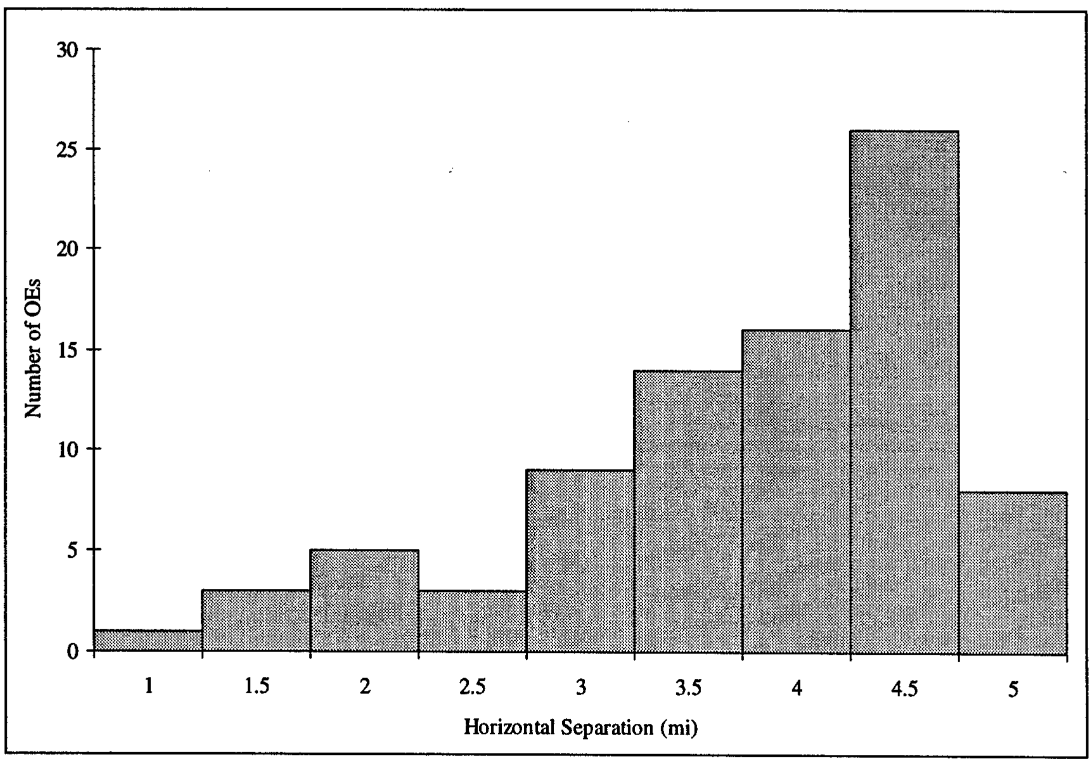

FIGURE 14. DISTRIBUTION OF OEs BY HORIZONTAL SEPARATION

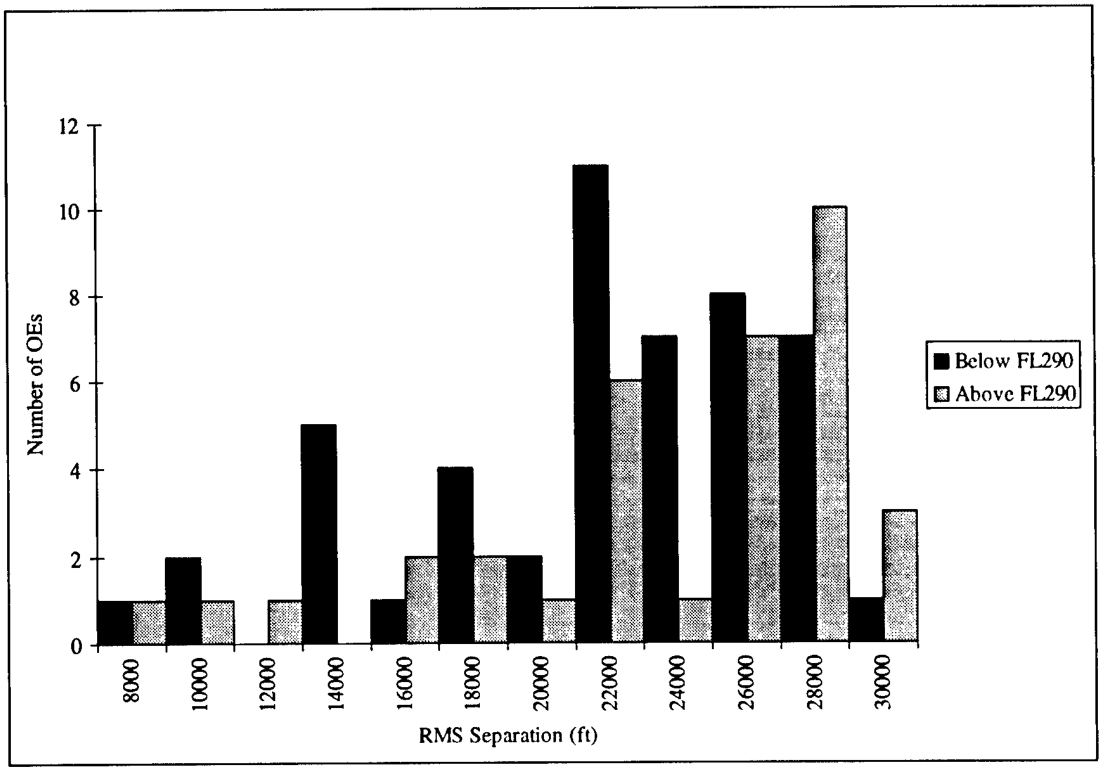

FIGURE 15. MINIMUM RMS SEPARATION FOR OEs

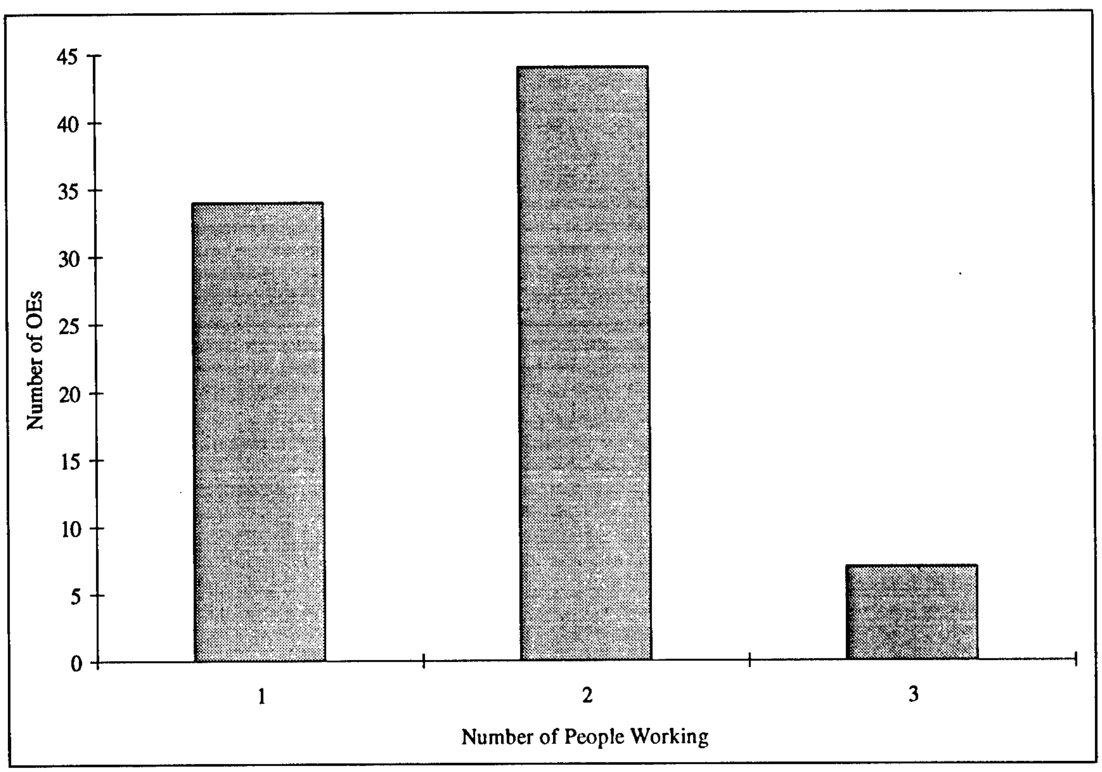

FIGURE 16. NUMBER OF CONTROLLERS WORKING AT THE TIME OF THE ERROR

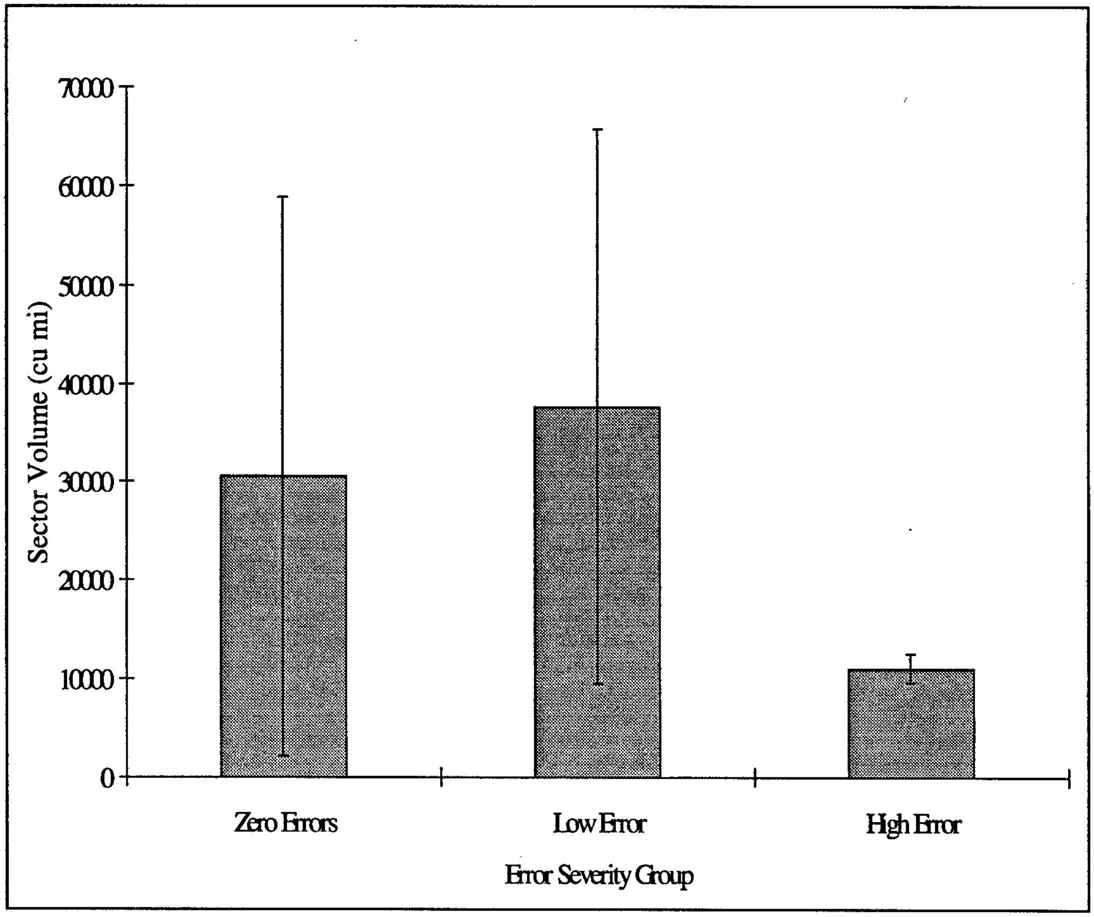

FIGURE 17. SECTOR VOLUME FOR OE ERROR GROUPS

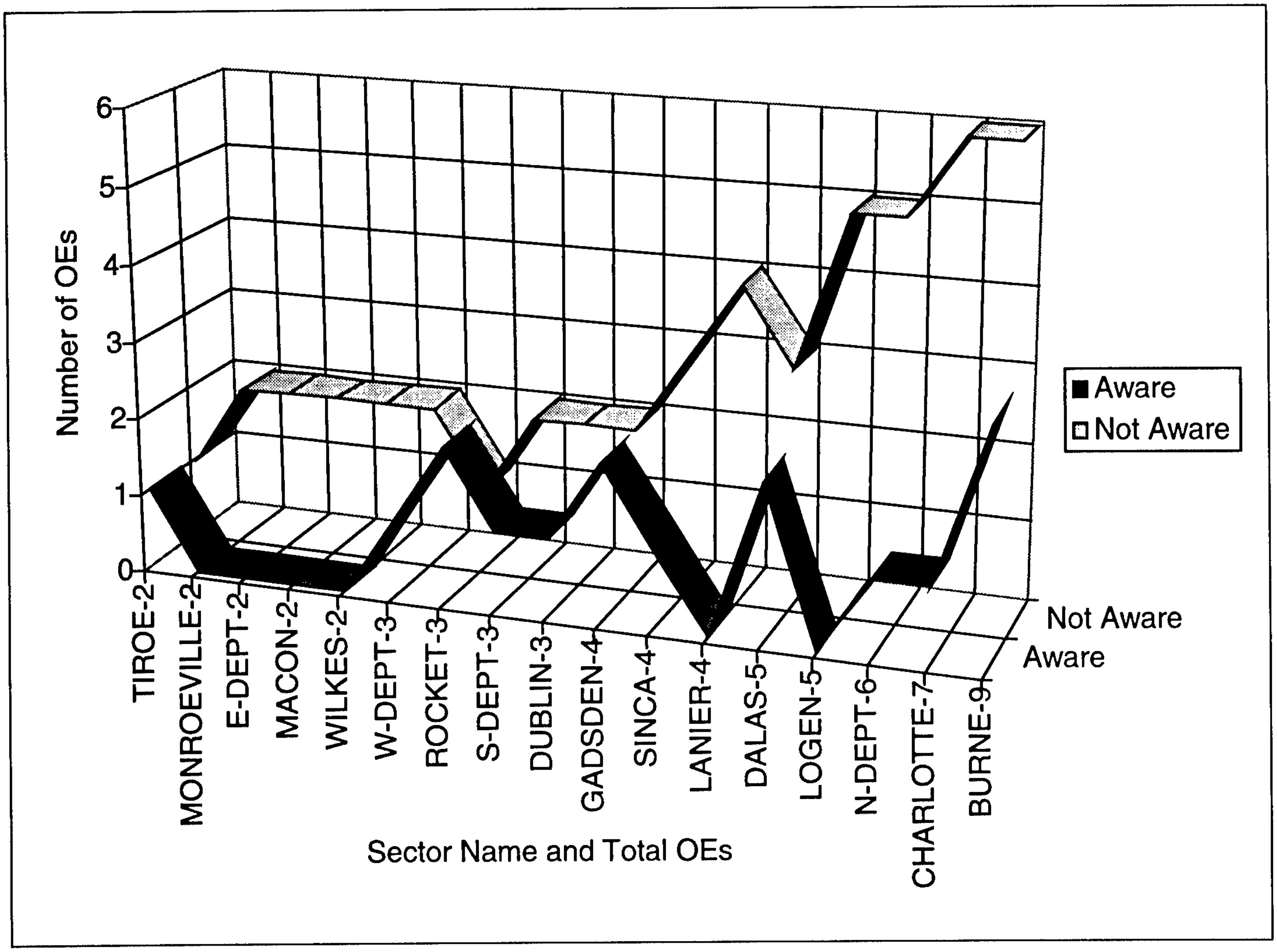

FIGURE 18. OE FREQUENCY FOR SA AND NO-SA ERRORS AS A FUNCTION OF TOTAL OEs

TABLES

TABLE 1. NUMBER OF OPERATIONAL ERRORS AS A FUNCTION OF TRAFFIC VOLUME AND WORKLOAD COMPLEXITY IN 1974-76 SEIS DATA

	Workload Complexity			
Traffic Volume	Light	Moderate	Heavy	Total
Light	127	68	9	204
Moderate	22	160	70	252
Heavy	0	14	73	87
Total	149	242	152	543

TABLE 2. MEASURES USED IN THE RODGERS AND MANNING (1995) STUDY

Measure	Type	Variable
Sector Activity	Handoff Activity	Number of Aircraft Transiting Sector
		Average Sector Transit Time
		Number of Handoffs Accepted
		Latency to Accept Handoffs
	Host computer system (HCS) Inputs	Number of HCS Inputs
		Number of Input Errors
Aircraft Proximity	Conflict Alert	Number of Conflict Alerts
		Duration of Conflict Alerts
	Proximity	Average Horizontal Separation
		Average Vertical Separation
		Number of Aircraft Pairs Within a Criterion Distance of Each Other Average Time Aircraft Pairs Spent Within a Criterion Distance of Each Other
	Load	Number of Aircraft in Sector by Track Type
Aircraft Dynamics	Speed, Altitude, and Heading	Average Change
		Number of State Changes
		Number of Aircraft Changing State
		Number of Change Over a Criterion Level

TABLE 3. MANOVA RESULTS

Variable	Result
Average Sector Transit Time	Increase
Average Latency to Accept Handoff	Increase
Number of Handoffs Accepted	Decrease
Average Vertical Separation	Increase
Average Time Aircraft Were Within 10 mi & 1000 ft	Increase

TABLE 4. SUMMARY OF LITERATURE REVIEW

Source	Factors or Issues
Arad (1964)	Conflicts related to rules of separation, average traffic speed, number of aircraft under control, sector size, and flow organization.
Arad, et al. (1964)	Routine load on controller affected by placement of sector boundaries with respect to traffic flow.
Siddiqee (1973)	Conflicts in en route airspace occur due to a loss of horizontal separation between aircraft at the same altitudes.
Schmidt (1976)	Conflicts predicted by traffic flow rate, separation standards, route geometry, aircraft speed, aircraft flow rate, angle of airway intersection, number of flight levels, and amount of transitioning traffic.
Couluris and Schmidt (1973)	Cost of sectorization is additional workload (coordination) imposed by placement of sector boundaries.
Empson (1987) Langan-Fox and Empson (1985)	Controller workload is related to airspace structure, procedural demands, traffic type, and control over task presentation rate.
Kinney, et al. (1977)	OEs occur under low to moderate workload and moderate complexity. In en route centers, 95% of errors attributed to attention, judgment, or communications. Most errors occur in level flight.
Schroeder (1982)	Most errors occur under light or moderate workload. Other aspects of the situation [sector factors?], apart from traffic volume, determine workload. Coordination is a direct or contributing factor in many errors.
Stager and Hameluck (1990) Stager, et al. (1989)	Definitions of direct and contributing causes. OEs occur under low to moderate workload conditions. Causes are attention, judgment, and communication problems.
Redding (1992)	Failure to maintain SA causes most errors under moderate traffic load. Communication, coordination, and misuse of radar data account for most errors.
Schroeder and Nye (1993)	OEs occur under average or lower traffic complexity. Problems with radar display, communication, coordination, and data posting most frequent causes.
Rodgers and Nye (1993)	Most OEs occur with one aircraft in level flight and another descending or ascending. Most moderate errors are between aircraft in level flight. Horizontal, not vertical, separation varies with severity. Higher horizontal separation for SA OEs.
Fowler (1980)	Sector complexity effected by problems with coordination, procedures, LOAs, and weather.
Buckley, et al. (1983)	Sector geometry and traffic density interact to affect controller performance.
Stein (1985)	Controller workload is related to clustering of aircraft in a small amount of airspace, number of hand-offs outbound/inbound, and total number of flights handled.

TABLE 4. SUMMARY OF LITERATURE REVIEW (CONTINUED)

Source	Factors or Issues
Grossberg (1989)	Sector complexity factors include control adjustments to merge and space aircraft, climbing and descending aircraft flight paths, mixture of aircraft types, frequent coordination, and heavy traffic.
Mogford, et al. (1993)	ATC complexity factors that may affect controller workload (and OEs): 1. Number of climbing and descending aircraft. 2. Degree of aircraft mix. 3. Number of intersecting flight paths. 4. Number of multiple functions controller must perform. 5. Number of required procedures controller must perform. 6. Number of military flights. 7. Frequency of contacts (coordination) or interface with other entities. 8. Extent to which controller is affected by airline hubbing. 9. Extent to which controller is affected by weather. 10. Number of complex aircraft routings. 11. Extent to which controller is affected by restricted, warning, and military operating areas. 12. Size of sector airspace. 13. Requirement for longitudinal sequencing and spacing. 14. Adequacy and reliability of radio and radar coverage. 15. Amount of radio frequency congestion. 16. Average amount of traffic.
Rodgers and Manning (1995)	OE time period shows increases in sector transit time, handoff acceptance latency, vertical separation, and aircraft density and decrease in number of handoffs accepted.

TABLE 5. FACTOR ANALYSIS RESULTS FOR SECTOR CHARACTERISTICS

Sector Variable	**Factor 1**	**Factor 2**	**Factor 3**	**Factor 4**	**Factor 5**	**Factor 6**
Variance Accounted For	**24%**	**22%**	**10%**	**7%**	**7%**	**4%**
Number of VORTACs	-0.05	0.24	0.21	**0.81**	-0.27	0.01
Number of shelves	0.09	**-0.54**	0.44	0.36	0.14	-0.20
Average complexity	**0.74**	0.21	-0.12	0.09	0.27	0.27
Average density	0.11	0.51	0.36	0.32	0.02	0.51
Traffic volume	**0.63**	0.50	-0.14	0.06	0.25	-0.16
Frequency congestion	**0.62**	0.48	-0.09	-0.20	0.12	0.11
Climbing/descending traffic	**0.84**	-0.31	-0.10	0.11	0.11	-0.13
Coordination	**0.48**	0.11	0.33	-0.19	-0.41	0.05
Multiple functions	**0.83**	0.13	0.30	-0.06	-0.15	-0.11
Hubbing	**0.55**	0.18	-0.38	0.12	0.51	-0.18
Number of intersections	0.34	-0.45	0.37	0.45	-0.20	0.17
Intersecting flight paths	**0.45**	0.38	0.34	-0.01	-0.22	-0.20
Complex routings	**0.55**	0.33	0.06	-0.05	-0.39	0.00
Miles of jetways	-0.47	**0.75**	0.22	0.00	0.15	-0.13
Miles of victor routes	-0.33	**0.88**	0.21	0.01	0.00	-0.09
Miles of other routes	-0.26	**0.86**	0.25	0.05	-0.07	-0.14
Percent of cube	0.15	-0.16	0.33	0.25	**0.57**	0.05
Military traffic	0.13	-0.21	**0.68**	-0.47	0.07	0.23
Restricted areas	0.10	-0.47	**0.48**	-0.23	0.31	0.21
Aircraft mix	0.18	**-0.73**	0.07	0.44	0.04	-0.24
Required procedures	**0.85**	0.19	0.17	-0.08	-0.12	-0.21
Radar/radio coverage	0.12	0.36	**-0.59**	0.31	-0.10	0.47
Cubic volume	-0.51	**0.61**	0.25	0.19	0.03	-0.12
Sector size	-0.29	**0.61**	0.24	0.08	0.47	-0.03
Sequencing and spacing	**0.57**	0.39	-0.32	0.06	-0.11	-0.09
Weather	**0.66**	0.29	0.11	-0.08	0.18	0.10

TABLE 6. PRIMARY CAUSAL FACTORS

Primary Causal Factor	**Number**	**Percent**
Radar display: Inappropriate use of displayed data: Other	36	42
Communication error	15	18
Radar display: Misidentification: Climbed aircraft with similar call sign	14	16
Radar display: Misidentification: Failure to maintain lateral separation	4	5
Radar display: Inappropriate use of displayed data: Mode C	4	5
Coordination	4	5
Data posting: Computer entry	3	4
Data posting: Flight progress strip	2	2
Radar display: Misidentification: Overlapping data blocks	2	2
Unknown	1	1

TABLE 7. SECONDARY CAUSAL FACTORS

Secondary Causal Factor	Number	Percent
Communication error	10	42
Radar display: Inappropriate use of displayed data	8	33
Coordination	5	21
Radar display: Misidentification: Climbed aircraft with similar call sign	1	4

TABLE 8. SUMMARY OF ALL CAUSAL FACTORS

Summary of Causal Factors	Number	Percent
Radar display	69	81
Communication error	25	29
Coordination	9	11
Data posting	5	6
Unknown	1	1

TABLE 9. CORRELATIONS OF SECTOR VARIABLES WITH NUMBER OF SECTOR OEs AND OE GROUP

	Correlations	
Variable	Number of OEs	OE Group
Number of major airports	N/A	$r_s = -.34, p = .021$
Number of VORTACs	$r = -.31, p = .042$	$r_s = -.25, p = .094$
Amount of climbing/descending traffic	$r = .33, p = .029$	$r_s = .29, p = .051$
Degree of aircraft mix	$r = -.28, p = .060$	$r_s = -.33, p = .025$
Number of multiple functions	$r = .33, p = .028$	$r_s = .26, p = .084$
Number of required procedures	$r = .38, p = .010$	$r_s = .33, p = .025$
Effect of airline hubbing	$r = .35, p = .020$	$r_s = .27, p = .073$
Weather	$r = .45, p = .002$	$r_s = .37, p = .012$
Number of complex aircraft routings	NS	$r_s = .29, p = .057$
Number of restricted areas	NS	$r_s = .24, p = .106$
Requirements for sequencing and spacing	NS	$r_s = .23, p = .129$
Radio frequency congestion	$r = .49, p = .001$	$r_s = .48, p = .001$
Average traffic volume	$r = .33, p = .025$	$r_s = .32, p = .033$
Total 16CF score (sum)	$r = .38, p = .010$	$r_s = .36, p = .015$
Average density	NS	$r_s = .26, p = .090$
Average complexity	$r = .42, p = .004$	$r_s = .51, p = .000$

TABLE 10. ANOVA TESTS FOR DIFFERENCES BETWEEN SECTOR CHARACTERISTICS

Variable	OE Group (mean)			F	p
	Zero	Low	High		
Amount of climbing/descending traffic	5.3	5.6	6.6	2.16	.128
Degree of aircraft mix	5.5	4.0	3.8	2.91	.066
Number of required procedures	4.5	5.1	6.0	2.78	.074
Weather	**4.7**	5.0	**6.1**	3.75	.032
Radio frequency congestion	**4.1**	5.2	**6.1**	6.20	.004
Average traffic volume	4.7	5.5	6.0	2.59	.087
Total 16CF score (sum)	**70.3**	75.7	**83.0**	3.13	.054
Average complexity	**269.3**	343.8	**465.0**	5.45	.008

TABLE 11. CORRELATIONS OF OE CHARACTERISTICS WITH NUMBER OF SECTOR OES AND OE FREQUENCY GROUP

Variable	Correlations	
	Number of OEs	OE Group (low & high only)
Number of aircraft in the sector	$r = .19$, $p = .084$	$r_s = .20$, $p = .067$
Complexity	$r = .28$, $p = .011$	$r_s = .25$, $p = .021$
Workload index	$r = .24$, $p = .027$	$r_s = .21$, $p = .052$
Vertical separation	$r = .20$, $p = .073$	NS
Position combined	N/A	$r_s = -.29$, $p = .007$

TABLE 12. REGRESSION ANALYSIS OF OE DATA

REGRESSION STATISTICS

MULTIPLE R	.58
MULTIPLE R^2	.34
ADJUSTED R^2	.31
SE OF ESTIMATE	1.73

ANALYSIS OF VARIANCE

	SS	df	MS	F RATIO
REGRESSION	64.77	2	32.39	10.82
RESIDUAL	125.67	42	2.99	p =.000

VARIABLES IN THE EQUATION

VARIABLE	b	SE	b	t	p (2 TAIL)
FREQ. CONG.	.76	.17	.56	4.37	.000
REST. AREAS	.34	.14	.32	2.47	.017
CONSTANT	64.59				

TABLE 13. RELATIONSHIP OF FINDINGS TO LITERATURE REVIEW

Source	Factors or Issues	Relevant Factors
Arad (1964)	Conflicts related to rules of separation, average traffic speed, number of aircraft under control, sector size, and flow organization.	Correlations with OE rate: Traffic volume higher, Complex routings higher, Sectors smaller in high OE sectors.
Arad, et al. (1964)	Routine load on controller affected by placement of sector boundaries with respect to traffic flow.	No relevant findings
Siddiqee (1973)	Conflicts in en route airspace occur due to a loss of horizontal separation between aircraft at the same altitudes.	SA errors had more horizontal separation than no-SA errors.
Schmidt (1976)	Conflicts predicted by traffic flow rate, separation standards, route geometry, aircraft speed, aircraft flow rate, angle of airway intersection, number of flight levels, and amount of transitioning traffic.	Correlations with OE rate: Traffic volume, Complex routings, Climbing/descending traffic.
Couluris and Schmidt (1973)	Cost of sectorization is additional workload (coordination) imposed by placement of sector boundaries.	Correlations with OE rate: (Coordination NS). Coordination problems cited in 11% of OEs.
Empson (1987) Langan-Fox and Empson (1985)	Controller workload is related to airspace structure, procedural demands, traffic type, and control over task presentation rate.	Correlations with OE rate: Complex routings, Required procedures, Aircraft mix.
Kinney, et al. (1977)	OEs occur under low to moderate workload and moderate complexity. In en route centers, 95% of errors attributed to attention, judgment, or communications. Most errors occur in level flight.	OEs occur with above average traffic load. Most OEs rated as moderately complex.
Schroeder (1982)	Most errors occur under light or moderate workload. Other aspects of the situation [sector factors?] apart from traffic volume determine workload. Coordination a direct or contributing factor in many errors.	OEs occur with above average traffic load. Most OEs rated as moderately complex. Coordination not correlated with error count but cited as cause in 11% of errors.
Stager and Hameluck (1990), Stager, et al. (1989)	Definitions of direct and contributing causes. OEs occur under low to moderate workload. Causes are attention, judgment, and communication problems.	OEs occur with above average traffic load. Most OEs rated as moderately complex.
Redding (1992)	Failure to maintain SA cause of most errors under moderate traffic load. Communication, coordination, and misuse of radar data account for most errors.	High error sectors also had many no-SA errors. Primary causes of OEs: 29% communication; 81% problems with radar display.
Schroeder and Nye (1993)	OEs occur under average or lower traffic complexity. Problems with radar display, communication, coordination, and data posting most frequent causes.	OEs occur with above average traffic load. Most OEs rated as moderately complex. Primary causes of OEs: 29% communication; 81% problems with radar display
Rodgers and Nye (1993)	Most OEs occur with one aircraft in level flight and another descending or ascending. Most moderate errors are between aircraft in level flight. Horizontal, not vertical, separation varies with severity. Higher horizontal separation for SA OEs.	SA errors had more horizontal separation than no-SA errors.

TABLE 13. RELATIONSHIP OF FINDINGS TO LITERATURE REVIEW (CONTINUED)

Source	Factors or Issues	Relevant Factors
Fowler (1980)	Sector complexity effected by problems with coordination, procedures, LOAs, and weather.	Correlations with OE rate: Complex routings Weather problems higher in high OE sectors.
Buckley, et al. (1983)	Sector geometry and traffic density interact to affect controller performance.	Correlations with OE rate: Traffic volume, Complex routings, Climbing/descending traffic
Stein (1985)	Controller workload related to clustering of aircraft in a small amount of airspace, number of hand-offs outbound/inbound, and total number of flights handled.	Correlations with OE rate: Traffic volume High error sectors were smaller
Grossberg (1989)	Sector complexity factors include control adjustments to merge and space aircraft, climbing and descending aircraft flight paths, mixture of aircraft types, frequent coordination, and heavy traffic.	Correlations with OE rate: (Sequencing/Spacing NS). Climbing/descending traffic, (Traffic mix NS). Traffic volume.
Mogford, et al. (1993) Mogford, et al. (1993)	ATC complexity factors that may affect controller workload (and OEs): 1. Number of climbing and descending aircraft. 2. Degree of aircraft mix 3. Number of intersecting flight paths 4. Number of multiple functions controller must perform. 5. Number of required procedures controller must perform. 6. Number of military flights. 7. Frequency of contacts (coordination) or interface with other entities. 8. Extent to which controller is affected by airline hubbing. 9. Extent to which controller is affected by weather. 10. Number of complex aircraft routings. 11. Extent to which controller is affected by restricted areas, warning areas, and military operating areas. 12. Size of sector airspace. 13. Requirement for longitudinal sequencing and spacing. 14. Adequacy and reliability of radio and radar coverage. 15. Amount of radio frequency congestion. 16. Average amount of traffic.	Correlations with OE rate: 1. Climbing/descending traffic, 2. (Traffic mix NS), 3. (Intersections NS), 4. Multiple functions, 5. Procedures, 6. (Military traffic NS), 7. (Coordination NS), 8 Hubbing, 9. Weather, 10. Complex routings, 11. Restricted areas, 12. (Size NS), 13. (Sequencing/spacing NS), 14. (Radio/radar coverage NS), 15. Frequency congestion, 16. Traffic volume. High OE sectors have more: Frequency congestion, Problem weather, Total complexity. Sectors smaller in high OE sectors.
Rodgers and Manning (1995)	OE time period shows increases in sector transit time, handoff acceptance latency, vertical separation, and aircraft density and decrease in number of handoffs accepted.	Aircraft volume higher at time of OE.

TABLE 14. COMPARISON OF OE CAUSES

Causal Factor	1985 to 1988 Data	1992 to 1995 Data
Radar Display	57%	81%
Communication	30%	29%
Coordination	30%	11%
Data Posting	20%	6%
Relief Briefing	4%	NA

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APPENDIX A:

PEARSON CORRELATION MATRIX OF SECTOR VARIABLES

- - Correlation Coefficients - -

	AVG_COM_	AVG_DEN_	CLDC	COOR	CUVOL	FPAPCT
AVG_COM_	1.0000 (45) P= .	.2762 (45) P= .066	.5744 (45) P= .000	.2129 (45) P= .160	-.2830 (45) P= .060	.1908 (45) P= .209
AVG_DEN_	.2762 (45) P= .066	1.0000 (45) P= .	-.0895 (45) P= .559	.1481 (45) P= .332	.3294 (45) P= .027	.1156 (45) P= .449
CLDC	.5744 (45) P= .000	-.0895 (45) P= .559	1.0000 (45) P= .	.3129 (45) P= .036	-.6169 (45) P= .000	.2218 (45) P= .143
COOR	.2129 (45) P= .160	.1481 (45) P= .332	.3129 (45) P= .036	1.0000 (45) P= .	-.1467 (45) P= .336	-.0196 (45) P= .898
CUVOL	-.2830 (45) P= .060	.3294 (45) P= .027	-.6169 (45) P= .000	-.1467 (45) P= .336	1.0000 (45) P= .	.0175 (45) P= .909
FPAPCT	.1908 (45) P= .209	.1156 (45) P= .449	.2218 (45) P= .143	-.0196 (45) P= .898	.0175 (45) P= .909	1.0000 (45) P= .
FREQ	.5430 (45) P= .000	.2178 (45) P= .151	.2537 (45) P= .093	.3168 (45) P= .034	-.0954 (45) P= .533	-.0245 (45) P= .873
FUNC	.5162 (45) P= .000	.2229 (45) P= .141	.6369 (45) P= .000	.5070 (45) P= .000	-.2088 (45) P= .169	.1233 (45) P= .420
HUB	.5288 (45) P= .000	-.0092 (45) P= .952	.5560 (45) P= .000	-.0005 (45) P= .997	-.1656 (45) P= .277	.1217 (45) P= .426
INTR	.3572 (45) P= .016	.2597 (45) P= .085	.1920 (45) P= .206	.3394 (45) P= .023	.0142 (45) P= .926	.0207 (45) P= .892
JET	-.2158 (45) P= .155	.3615 (45) P= .015	-.5612 (45) P= .000	-.1441 (45) P= .345	.7146 (45) P= .000	-.0935 (45) P= .541

(Coefficient / (Cases) / 2-tailed Significance)
" . " is printed if a coefficient cannot be computed

- - Correlation Coefficients - -

	AVG_COM_	AVG_DEN_	CLDC	COOR	CUVOL	FPAPCT
MIL	-.0172 (45) P= .911	.0710 (45) P= .643	.0260 (45) P= .865	.2505 (45) P= .097	-.1182 (45) P= .439	.1326 (45) P= .385
MIX	-.0332 (45) P= .828	-.2633 (45) P= .081	.4821 (45) P= .001	-.0702 (45) P= .647	-.3913 (45) P= .008	.2453 (45) P= .104
NOINTSX	.0947 (45) P= .536	.0768 (45) P= .616	.2984 (45) P= .046	.2602 (45) P= .084	-.2963 (45) P= .048	.2063 (45) P= .174
OTHRTS	-.0839 (45) P= .584	.4267 (45) P= .003	-.4620 (45) P= .001	.1087 (45) P= .477	.7272 (45) P= .000	-.1144 (45) P= .454
PROC	.5239 (45) P= .000	.1773 (45) P= .244	.6650 (45) P= .000	.5227 (45) P= .000	-.2464 (45) P= .103	.1099 (45) P= .472
RAD	.2989 (45) P= .046	.2839 (45) P= .059	.0556 (45) P= .717	-.0797 (45) P= .603	.0588 (45) P= .701	-.1347 (45) P= .378
REST	.0476 (45) P= .756	.0267 (45) P= .862	.2230 (45) P= .141	.0021 (45) P= .989	-.2451 (45) P= .105	.2471 (45) P= .102
RTNG	.3271 (45) P= .028	.1986 (45) P= .191	.3279 (45) P= .028	.3562 (45) P= .016	-.0216 (45) P= .888	-.2108 (45) P= .165
SHELF	-.1221 (45) P= .424	-.0755 (45) P= .622	.2558 (45) P= .090	-.0442 (45) P= .773	-.1605 (45) P= .292	.2990 (45) P= .046
SIZE	.0080 (45) P= .959	.3072 (45) P= .040	-.3856 (45) P= .009	-.1413 (45) P= .354	.5719 (45) P= .000	.1399 (45) P= .359
SQ_SP	.4424 (45) P= .002	.1495 (45) P= .327	.3634 (45) P= .014	.1680 (45) P= .270	-.0320 (45) P= .835	-.0826 (45) P= .590

(Coefficient / (Cases) / 2-tailed Significance)

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- - Correlation Coefficients - -

	AVG_COM_	AVG_DEN_	CLDC	COOR	CUVOL	FPAPCT
TOTALOE	.4189 (45) P= .004	.2108 (45) P= .165	.3259 (45) P= .029	.1482 (45) P= .331	-.1354 (45) P= .375	.1073 (45) P= .483
TOTCOMX	.6951 (45) P= .000	.2521 (45) P= .095	.7285 (45) P= .000	.4835 (45) P= .001	-.2623 (45) P= .082	.1533 (45) P= .315
VICTOR	-.1124 (45) P= .462	.4612 (45) P= .001	-.5220 (45) P= .000	.0198 (45) P= .898	.7778 (45) P= .000	-.1142 (45) P= .455
VOL	.5943 (45) P= .000	.2614 (45) P= .083	.3938 (45) P= .007	.1560 (45) P= .306	-.0806 (45) P= .599	-.0023 (45) P= .988
VORTAC	.0307 (45) P= .842	.3663 (45) P= .013	-.0800 (45) P= .602	-.0011 (45) P= .994	.2872 (45) P= .056	-.0075 (45) P= .961
WX	.5641 (45) P= .000	.1766 (45) P= .246	.4149 (45) P= .005	.3467 (45) P= .020	-.2065 (45) P= .174	.1607 (45) P= .292

(Coefficient / (Cases) / 2-tailed Significance)

" . " is printed if a coefficient cannot be computed

- - Correlation Coefficients - -

	FREQ	FUNC	HUB	INTR	JET	MIL
AVG_COM_	.5430	.5162	.5288	.3572	-.2158	-.0172
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .000	P= .000	P= .016	P= .155	P= .911
AVG_DEN_	.2178	.2229	-.0092	.2597	.3615	.0710
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .151	P= .141	P= .952	P= .085	P= .015	P= .643
CLDC	.2537	.6369	.5560	.1920	-.5612	.0260
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .093	P= .000	P= .000	P= .206	P= .000	P= .865
COOR	.3168	.5070	-.0005	.3394	-.1441	.2505
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .034	P= .000	P= .997	P= .023	P= .345	P= .097
CUVOL	-.0954	-.2088	-.1656	.0142	.7146	-.1182
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .533	P= .169	P= .277	P= .926	P= .000	P= .439
FPAPCT	-.0245	.1233	.1217	.0207	-.0935	.1326
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .873	P= .420	P= .426	P= .892	P= .541	P= .385
FREQ	1.0000	.5291	.4819	.3704	.0315	.0269
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .	P= .000	P= .001	P= .012	P= .837	P= .861
FUNC	.5291	1.0000	.2319	.5898	-.2477	.2592
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .	P= .125	P= .000	P= .101	P= .086
HUB	.4819	.2319	1.0000	.0784	-.0944	-.2476
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .001	P= .125	P= .	P= .609	P= .537	P= .101
INTR	.3704	.5898	.0784	1.0000	.1128	.1158
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .012	P= .000	P= .609	P= .	P= .461	P= .449
JET	.0315	-.2477	-.0944	.1128	1.0000	-.0992
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .837	P= .101	P= .537	P= .461	P= .	P= .517

(Coefficient / (Cases) / 2-tailed Significance)

" . " is printed if a coefficient cannot be computed

- - Correlation Coefficients - -

	FREQ	FUNC	HUB	INTR	JET	MIL
MIL	.0269	.2592	-.2476	.1158	-.0992	1.0000
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .861	P= .086	P= .101	P= .449	P= .517	P= .
MIX	-.4366	.0880	.0710	-.1456	-.5476	.0445
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .003	P= .565	P= .643	P= .340	P= .000	P= .772
NOINTSX	.0101	.2497	-.0721	.0292	-.4776	.1858
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .947	P= .098	P= .638	P= .849	P= .001	P= .222
OTHRTS	.1693	-.0369	-.0791	.2528	.8466	-.1221
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .266	P= .810	P= .606	P= .094	P= .000	P= .424
PROC	.5505	.8828	.3623	.5121	-.2100	.1406
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .000	P= .014	P= .000	P= .166	P= .357
RAD	.2495	-.0175	.2669	-.1016	.0277	-.4327
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .098	P= .909	P= .076	P= .507	P= .857	P= .003
REST	-.2176	.1059	-.0110	.0000	-.2146	.5929
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .151	P= .489	P= .943	P=1.000	P= .157	P= .000
RTNG	.3763	.5365	.2158	.3050	-.0112	.1385
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .011	P= .000	P= .155	P= .042	P= .942	P= .364
SHELF	-.2077	.0914	-.0376	-.1514	-.3105	.2802
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .171	P= .550	P= .806	P= .321	P= .038	P= .062
SIZE	.1444	-.1416	.1047	.0096	.6547	.0560
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .344	P= .353	P= .494	P= .950	P= .000	P= .715
SQ_SP	.4325	.4313	.4593	.3193	-.1510	-.1842
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .003	P= .003	P= .002	P= .033	P= .322	P= .226

(Coefficient / (Cases) / 2-tailed Significance)

" . " is printed if a coefficient cannot be computed

- - Correlation Coefficients - -

	FREQ	FUNC	HUB	INTR	JET	MIL
TOTALOE	.4943	.3280	.3453	.1375	.0374	.0418
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .001	P= .028	P= .020	P= .368	P= .807	P= .785
TOTCOMX	.6542	.8331	.6129	.5236	-.1994	.2320
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .000	P= .000	P= .000	P= .189	P= .125
VICTOR	.1622	-.0895	-.0551	.2845	.8879	-.0951
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .287	P= .559	P= .719	P= .058	P= .000	P= .534
VOL	.6815	.5107	.6355	.3882	.1451	-.1795
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .000	P= .000	P= .008	P= .342	P= .238
VORTAC	-.1057	.0149	-.0878	.2792	.2162	-.2835
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .490	P= .923	P= .566	P= .063	P= .154	P= .059
WX	.6244	.4854	.3879	.3248	-.0322	.2020
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .001	P= .008	P= .030	P= .834	P= .183

(Coefficient / (Cases) / 2-tailed Significance)

" . " is printed if a coefficient cannot be computed

-- Correlation Coefficients --

	MIX	NOINTSX	OTHRTS	PROC	RAD	REST
AVG_COM_	-.0332 (45) P= .828	.0947 (45) P= .536	-.0839 (45) P= .584	.5239 (45) P= .000	.2989 (45) P= .046	.0476 (45) P= .756
AVG_DEN_	-.2633 (45) P= .081	.0768 (45) P= .616	.4267 (45) P= .003	.1773 (45) P= .244	.2839 (45) P= .059	.0267 (45) P= .862
CLDC	.4821 (45) P= .001	.2984 (45) P= .046	-.4620 (45) P= .001	.6650 (45) P= .000	.0556 (45) P= .717	.2230 (45) P= .141
COOR	-.0702 (45) P= .647	.2602 (45) P= .084	.1087 (45) P= .477	.5227 (45) P= .000	-.0797 (45) P= .603	.0021 (45) P= .989
CUVOL	-.3913 (45) P= .008	-.2963 (45) P= .048	.7272 (45) P= .000	-.2464 (45) P= .103	.0588 (45) P= .701	-.2451 (45) P= .105
FPAPCT	.2453 (45) P= .104	.2063 (45) P= .174	-.1144 (45) P= .454	.1099 (45) P= .472	-.1347 (45) P= .378	.2471 (45) P= .102
FREQ	-.4366 (45) P= .003	.0101 (45) P= .947	.1693 (45) P= .266	.5505 (45) P= .000	.2495 (45) P= .098	-.2176 (45) P= .151
FUNC	.0880 (45) P= .565	.2497 (45) P= .098	-.0369 (45) P= .810	.8828 (45) P= .000	-.0175 (45) P= .909	.1059 (45) P= .489
HUB	.0710 (45) P= .643	-.0721 (45) P= .638	-.0791 (45) P= .606	.3623 (45) P= .014	.2669 (45) P= .076	-.0110 (45) P= .943
INTR	-.1456 (45) P= .340	.0292 (45) P= .849	.2528 (45) P= .094	.5121 (45) P= .000	-.1016 (45) P= .507	.0000 (45) P=1.000
JET	-.5476 (45) P= .000	-.4776 (45) P= .001	.8466 (45) P= .000	-.2100 (45) P= .166	.0277 (45) P= .857	-.2146 (45) P= .157

(Coefficient / (Cases) / 2-tailed Significance)

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- - Correlation Coefficients - -

	MIX	NOINTSX	OTHRTS	PROC	RAD	REST
MIL	.0445 (45) P= .772	.1858 (45) P= .222	-.1221 (45) P= .424	.1406 (45) P= .357	-.4327 (45) P= .003	.5929 (45) P= .000
MIX	1.0000 (45) P= .	.4975 (45) P= .001	-.6258 (45) P= .000	.0499 (45) P= .745	-.2040 (45) P= .179	.2625 (45) P= .082
NOINTSX	.4975 (45) P= .001	1.0000 (45) P= .	-.3431 (45) P= .021	.1686 (45) P= .268	-.1741 (45) P= .253	.2560 (45) P= .090
OTHRTS	-.6258 (45) P= .000	-.3431 (45) P= .021	1.0000 (45) P= .	.0495 (45) P= .747	.1064 (45) P= .487	-.4039 (45) P= .006
PROC	.0499 (45) P= .745	.1686 (45) P= .268	.0495 (45) P= .747	1.0000 (45) P= .	.0028 (45) P= .986	.0180 (45) P= .907
RAD	-.2040 (45) P= .179	-.1741 (45) P= .253	.1064 (45) P= .487	.0028 (45) P= .986	1.0000 (45) P= .	-.4421 (45) P= .002
REST	.2625 (45) P= .082	.2560 (45) P= .090	-.4039 (45) P= .006	.0180 (45) P= .907	-.4421 (45) P= .002	1.0000 (45) P= .
RTNG	-.1618 (45) P= .288	.1139 (45) P= .456	.2106 (45) P= .165	.5460 (45) P= .000	.2088 (45) P= .169	-.1153 (45) P= .451
SHELF	.5947 (45) P= .000	.5237 (45) P= .000	-.3032 (45) P= .043	.0297 (45) P= .846	-.4060 (45) P= .006	.2873 (45) P= .056
SIZE	-.3966 (45) P= .007	-.3113 (45) P= .037	.6077 (45) P= .000	-.1728 (45) P= .256	.0071 (45) P= .963	-.1132 (45) P= .459
SQ_SP	-.1417 (45) P= .353	-.0713 (45) P= .641	.0907 (45) P= .554	.5229 (45) P= .000	.3489 (45) P= .019	-.2600 (45) P= .085

(Coefficient / (Cases) / 2-tailed Significance)

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- - Correlation Coefficients - -

	MIX	NOINTSX	OTHRTS	PROC	RAD	REST
TOTALOE	-.2827 (45) P= .060	-.1273 (45) P= .405	-.0004 (45) P= .998	.3818 (45) P= .010	-.0129 (45) P= .933	.1946 (45) P= .200
TOTCOMX	.0646 (45) P= .673	.2160 (45) P= .154	-.0137 (45) P= .929	.8419 (45) P= .000	.1291 (45) P= .398	.1390 (45) P= .362
VICTOR	-.6223 (45) P= .000	-.4634 (45) P= .001	.9054 (45) P= .000	-.0583 (45) P= .704	.1542 (45) P= .312	-.3226 (45) P= .031
VOL	-.1948 (45) P= .200	-.0138 (45) P= .928	.2226 (45) P= .142	.5653 (45) P= .000	.2156 (45) P= .155	-.1715 (45) P= .260
VORTAC	.1241 (45) P= .417	.3588 (45) P= .015	.2923 (45) P= .051	-.0470 (45) P= .759	.2068 (45) P= .173	-.2130 (45) P= .160
WX	-.1692 (45) P= .266	.1482 (45) P= .331	.1434 (45) P= .347	.5197 (45) P= .000	.0904 (45) P= .555	-.1058 (45) P= .489

(Coefficient / (Cases) / 2-tailed Significance)

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- - Correlation Coefficients - -

	RTNG	SHELF	SIZE	SQ_SP	TOTALOE	TOTCOMX
AVG_COM_	.3271	-.1221	.0080	.4424	.4189	.6951
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .028	P= .424	P= .959	P= .002	P= .004	P= .000
AVG_DEN_	.1986	-.0755	.3072	.1495	.2108	.2521
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .191	P= .622	P= .040	P= .327	P= .165	P= .095
CLDC	.3279	.2558	-.3856	.3634	.3259	.7285
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .028	P= .090	P= .009	P= .014	P= .029	P= .000
COOR	.3562	-.0442	-.1413	.1680	.1482	.4835
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .016	P= .773	P= .354	P= .270	P= .331	P= .001
CUVOL	-.0216	-.1605	.5719	-.0320	-.1354	-.2623
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .888	P= .292	P= .000	P= .835	P= .375	P= .082
FPAPCT	-.2108	.2990	.1399	-.0826	.1073	.1533
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .165	P= .046	P= .359	P= .590	P= .483	P= .315
FREQ	.3763	-.2077	.1444	.4325	.4943	.6542
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .011	P= .171	P= .344	P= .003	P= .001	P= .000
FUNC	.5365	.0914	-.1416	.4313	.3280	.8331
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .550	P= .353	P= .003	P= .028	P= .000
HUB	.2158	-.0376	.1047	.4593	.3453	.6129
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .155	P= .806	P= .494	P= .002	P= .020	P= .000
INTR	.3050	-.1514	.0096	.3193	.1375	.5236
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .042	P= .321	P= .950	P= .033	P= .368	P= .000
JET	-.0112	-.3105	.6547	-.1510	.0374	-.1994
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .942	P= .038	P= .000	P= .322	P= .807	P= .189

(Coefficient / (Cases) / 2-tailed Significance)

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- - Correlation Coefficients - -

	RTNG	SHELF	SIZE	SQ_SP	TOTALOE	TOTCOMX
MIL	.1385 (45) P= .364	.2802 (45) P= .062	.0560 (45) P= .715	-.1842 (45) P= .226	.0418 (45) P= .785	.2320 (45) P= .125
MIX	-.1618 (45) P= .288	.5947 (45) P= .000	-.3966 (45) P= .007	-.1417 (45) P= .353	-.2827 (45) P= .060	.0646 (45) P= .673
NOINTSX	.1139 (45) P= .456	.5237 (45) P= .000	-.3113 (45) P= .037	-.0713 (45) P= .641	-.1273 (45) P= .405	.2160 (45) P= .154
OTHRTS	.2106 (45) P= .165	-.3032 (45) P= .043	.6077 (45) P= .000	.0907 (45) P= .554	-.0004 (45) P= .998	-.0137 (45) P= .929
PROC	.5460 (45) P= .000	.0297 (45) P= .846	-.1728 (45) P= .256	.5229 (45) P= .000	.3818 (45) P= .010	.8419 (45) P= .000
RAD	.2088 (45) P= .169	-.4060 (45) P= .006	.0071 (45) P= .963	.3489 (45) P= .019	-.0129 (45) P= .933	.1291 (45) P= .398
REST	-.1153 (45) P= .451	.2873 (45) P= .056	-.1132 (45) P= .459	-.2600 (45) P= .085	.1946 (45) P= .200	.1390 (45) P= .362
RTNG	1.0000 (45) P= .	-.0880 (45) P= .566	-.1130 (45) P= .460	.5172 (45) P= .000	.2363 (45) P= .118	.6004 (45) P= .000
SHELF	-.0880 (45) P= .566	1.0000 (45) P= .	-.1619 (45) P= .288	-.3071 (45) P= .040	-.0684 (45) P= .655	.0283 (45) P= .854
SIZE	-.1130 (45) P= .460	-.1619 (45) P= .288	1.0000 (45) P= .	.0020 (45) P= .990	-.1221 (45) P= .424	.0108 (45) P= .944
SQ_SP	.5172 (45) P= .000	-.3071 (45) P= .040	.0020 (45) P= .990	1.0000 (45) P= .	.0929 (45) P= .544	.6180 (45) P= .000

(Coefficient / (Cases) / 2-tailed Significance)

" . " is printed if a coefficient cannot be computed

- - Correlation Coefficients - -

	RTNG	SHELF	SIZE	SQ_SP	TOTALOE	TOTCOMX
TOTALOE	.2363	-.0684	-.1221	.0929	1.0000	.3821
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .118	P= .655	P= .424	P= .544	P= .	P= .010
TOTCOMX	.6004	.0283	.0108	.6180	.3821	1.0000
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .000	P= .854	P= .944	P= .000	P= .010	P= .
VICTOR	.1317	-.4125	.6531	.1144	-.0241	-.0382
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .389	P= .005	P= .000	P= .454	P= .875	P= .803
VOL	.3808	-.1708	.2043	.5330	.3338	.7066
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .010	P= .262	P= .178	P= .000	P= .025	P= .000
VORTAC	.0899	.1623	.1994	.0718	-.3050	.0157
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .557	P= .287	P= .189	P= .639	P= .042	P= .918
WX	.3781	.0182	.0843	.3606	.4493	.6685
	(45)	(45)	(45)	(45)	(45)	(45)
	P= .010	P= .905	P= .582	P= .015	P= .002	P= .000

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- - Correlation Coefficients - -

	VICTOR	VOL	VORTAC	WX
AVG_COM_	-.1124	.5943	.0307	.5641
	(45)	(45)	(45)	(45)
	P= .462	P= .000	P= .842	P= .000
AVG_DEN_	.4612	.2614	.3663	.1766
	(45)	(45)	(45)	(45)
	P= .001	P= .083	P= .013	P= .246
CLDC	-.5220	.3938	-.0800	.4149
	(45)	(45)	(45)	(45)
	P= .000	P= .007	P= .602	P= .005
COOR	.0198	.1560	-.0011	.3467
	(45)	(45)	(45)	(45)
	P= .898	P= .306	P= .994	P= .020
CUVOL	.7778	-.0806	.2872	-.2065
	(45)	(45)	(45)	(45)
	P= .000	P= .599	P= .056	P= .174
FPAPCT	-.1142	-.0023	-.0075	.1607
	(45)	(45)	(45)	(45)
	P= .455	P= .988	P= .961	P= .292
FREQ	.1622	.6815	-.1057	.6244
	(45)	(45)	(45)	(45)
	P= .287	P= .000	P= .490	P= .000
FUNC	-.0895	.5107	.0149	.4854
	(45)	(45)	(45)	(45)
	P= .559	P= .000	P= .923	P= .001
HUB	-.0551	.6355	-.0878	.3879
	(45)	(45)	(45)	(45)
	P= .719	P= .000	P= .566	P= .008
INTR	.2845	.3882	.2792	.3248
	(45)	(45)	(45)	(45)
	P= .058	P= .008	P= .063	P= .030
JET	.8879	.1451	.2162	-.0322
	(45)	(45)	(45)	(45)
	P= .000	P= .342	P= .154	P= .834

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- - Correlation Coefficients - -

	VICTOR	VOL	VORTAC	WX
MIL	-.0951	-.1795	-.2835	.2020
	(45)	(45)	(45)	(45)
	P= .534	P= .238	P= .059	P= .183
MIX	-.6223	-.1948	.1241	-.1692
	(45)	(45)	(45)	(45)
	P= .000	P= .200	P= .417	P= .266
NOINTSX	-.4634	-.0138	.3588	.1482
	(45)	(45)	(45)	(45)
	P= .001	P= .928	P= .015	P= .331
OTHRTS	.9054	.2226	.2923	.1434
	(45)	(45)	(45)	(45)
	P= .000	P= .142	P= .051	P= .347
PROC	-.0583	.5653	-.0470	.5197
	(45)	(45)	(45)	(45)
	P= .704	P= .000	P= .759	P= .000
RAD	.1542	.2156	.2068	.0904
	(45)	(45)	(45)	(45)
	P= .312	P= .155	P= .173	P= .555
REST	-.3226	-.1715	-.2130	-.1058
	(45)	(45)	(45)	(45)
	P= .031	P= .260	P= .160	P= .489
RTNG	.1317	.3808	.0899	.3781
	(45)	(45)	(45)	(45)
	P= .389	P= .010	P= .557	P= .010
SHELF	-.4125	-.1708	.1623	.0182
	(45)	(45)	(45)	(45)
	P= .005	P= .262	P= .287	P= .905
SIZE	.6531	.2043	.1994	.0843
	(45)	(45)	(45)	(45)
	P= .000	P= .178	P= .189	P= .582
SQ_SP	.1144	.5330	.0718	.3606
	(45)	(45)	(45)	(45)
	P= .454	P= .000	P= .639	P= .015

(Coefficient / (Cases) / 2-tailed Significance)

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- - Correlation Coefficients - -

	VICTOR	VOL	VORTAC	WX
TOTALOE	-.0241	.3338	-.3050	.4493
	(45)	(45)	(45)	(45)
	P= .875	P= .025	P= .042	P= .002
TOTCOMX	-.0382	.7066	.0157	.6685
	(45)	(45)	(45)	(45)
	P= .803	P= .000	P= .918	P= .000
VICTOR	1.0000	.2232	.2596	-.0013
	(45)	(45)	(45)	(45)
	P= .	P= .141	P= .085	P= .993
VOL	.2232	1.0000	.0238	.5155
	(45)	(45)	(45)	(45)
	P= .141	P= .	P= .876	P= .000
VORTAC	.2596	.0238	1.0000	-.0232
	(45)	(45)	(45)	(45)
	P= .085	P= .876	P= .	P= .880
WX	-.0013	.5155	-.0232	1.0000
	(45)	(45)	(45)	(45)
	P= .993	P= .000	P= .880	P= .

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